REPORT DOCUMENTATION PAGE	*Form Approved* *OMB No. 0704-0188*

1. AGENCY USE ONLY *(Leave blank)*

2. REPORT DATE
14.Jan.03

3. REPORT TYPE AND DATES COVERED
THESIS

4. TITLE AND SUBTITLE
SYSTEM DESIGN IMPLEMENTATION IN THE AIRCRAFT MANUFACTURING INDUSTRY

5. FUNDING NUMBERS

6. AUTHOR(S)
CAPT HENDRICKS STEVEN D

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
MASSACHUSETTS INSTITUTE OF TECHNOLOGY

8. PERFORMING ORGANIZATION REPORT NUMBER
CI02-825

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)
THE DEPARTMENT OF THE AIR FORCE
AFIT/CIA, BLDG 125
2950 P STREET
WPAFB OH 45433

10. SPONSORING/MONITORING AGENCY REPORT NUMBER

11. SUPPLEMENTARY NOTES

12a. DISTRIBUTION AVAILABILITY STATEMENT
Unlimited distribution
In Accordance With AFI 35-205/AFIT Sup 1

12b. DISTRIBUTION CODE

13. ABSTRACT *(Maximum 200 words)*

DISTRIBUTION STATEMENT A
Approved for Public Release
Distribution Unlimited

20030225 097

14. SUBJECT TERMS

15. NUMBER OF PAGES
105

16. PRICE CODE

17. SECURITY CLASSIFICATION OF REPORT	18. SECURITY CLASSIFICATION OF THIS PAGE	19. SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT

System Design Implementation in the Aircraft Manufacturing Industry

by
Steven D. Hendricks

B.S. Engineering Mechanics
United States Air Force Academy, 1996

Submitted to the System Design and Management Program
in Partial Fulfillment of the Requirements for the Degree of

Master of Science in Engineering and Management

at the
Massachusetts Institute of Technology

September 2002

Signature of Author ____________________
Steven D. Hendricks
System Design and Management Program
September 2002

Certified by ____________________
David S. Cochran
Thesis Supervisor
Associate Professor of Mechanical Engineering

Accepted by ____________________
Steven D. Eppinger
Co-Director, LFM/SDM
GM LFM Professor of Management Science and Engineering Systems

Accepted by ____________________
Paul A. Lagace
Co-Director, LFM/SDM
Professor of Aeronautics & Astronautics and Engineering Systems

THIS PAGE INTENTIONALLY LEFT BLANK

System Design Implementation in the Aircraft Manufacturing Industry

by
Steven D. Hendricks

Submitted to the System Design and Management Program
On August 9, 2002 in Partial Fulfillment of the
Requirements for the Degree of

Master of Science in Engineering and Management

ABSTRACT

The central theme of this thesis is that desired business results are the direct result of the system design (Cochran, et. al, April 2002). It is also theorized that the 'thinking' within an organization creates the organization's 'structure' or design, which then drives the system's 'behavior' (Cochran, et. al, April 2002). It is concluded that the behavior, actions, performance, quality, cost, culture and classifications describing systems as either 'mass' or 'lean' are solely the results of the system's design or structure. Achievement of enduring change in a system's performance must begin with a change in the thinking of all the people in the enterprise, but especially that of leadership. In the absence of such a change in the thinking, the needed structural change within the system will be short-lived, only resulting in localized optimization of sub-systems versus systemic improvement.

Two types of thinking, 'mass thinking' and 'system thinking,' are defined and analyzed with respect to their structure and resulting behavior. The unit cost equation exemplifies the structure within mass systems resulting in business results being more unpredictable. Axiomatic design is presented as the way of structuring or design methodology to best reflect, understand and control the complexity inherent in the design of large-scale integrated systems. System stability is identified as the desired objective of system design.

The Product Delivery System (PDS) is applied in a case study comparing the 'before' and 'after' state of the redesign of a manufacturing cell. Direct correlation is identified between achievement of PDS requirements and improved system performance. Research based on the logical system design as defined by the PDS also was used to develop and apply an investment and resource allocation methodology to support manufacturing system design implementation. The methodology is a new approach that can be used by a company with constrained investment resources to target and prioritize potential continuous improvement projects to most effectively apply limited resources to ensure the greatest increase in system stability.

Thesis Supervisor: David S. Cochran

Title: Associate Professor of Mechanical Engineering

THIS PAGE INTENTIONALLY LEFT BLANK

THIS PAGE INTENTIONALLY LEFT BLANK

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

LIST OF EQUATIONS

CHAPTER 1 INTRODUCTION

1.1 Thesis Motivation

In October of 2001, the U.S. Government awarded the Joint Strike Fighter production contract, the largest production contract ever awarded by the Department of Defense, to Lockheed Martin. Various estimates place the total lifetime value of the contract, including potential foreign military sales, to be as high as $400 billion over the next 30 years [CNN, 2001]. Nearly one year prior to actual announcement of the winner, the U.S. government delayed the decision to allow more time to determine which of the two competing companies, Lockheed Martin or Boeing, was more 'lean.' Why did the decision have to be delayed? The author proposes that the government was unable to assess the 'leanness' of either company because the government had difficulty defining 'lean' with thorough and objective criteria.

Over the past three decades and for the next two, the U.S. military's acquisition of the fighter aircraft has and will undergo significant changes (see Figure 1-1) (Roche, 2002).

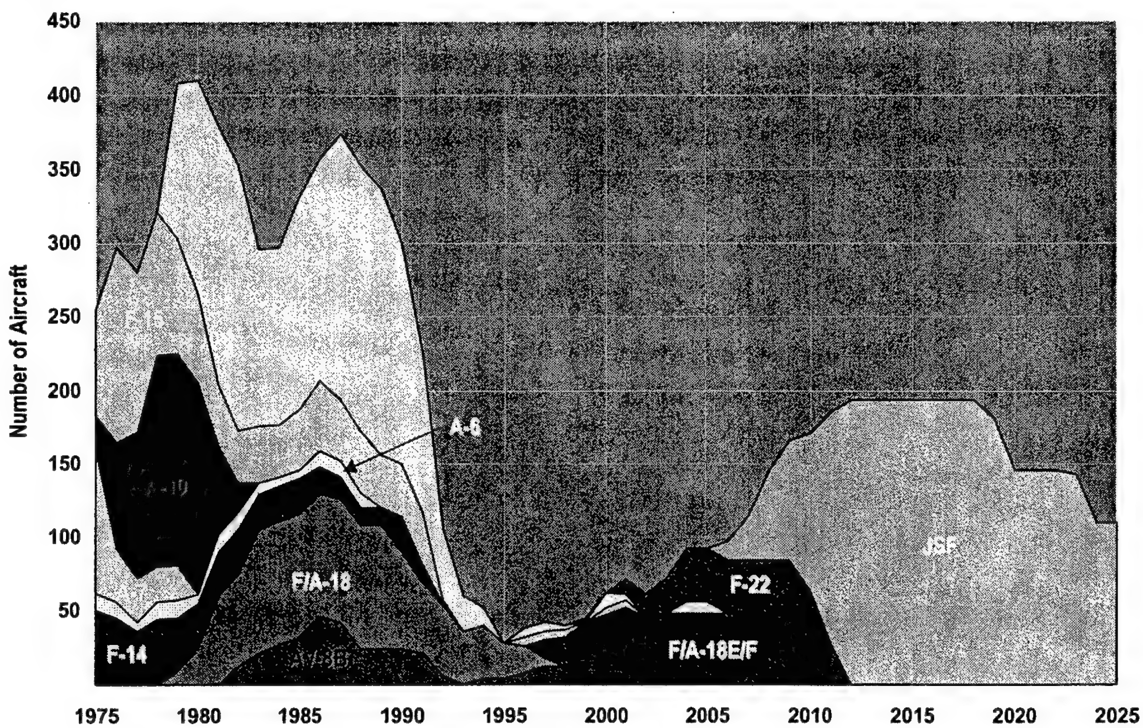


Figure 1-1 U.S. Fighter Procurement Quantities

From the 1980s ramp up by President Reagan to the massive cutback by the Clinton administration in the 1990s, not only has there been a highly variable number of fighter aircraft purchased per year, but also the number of available major defense contractors, specifically for aircraft integration (General Dynamics, McDonnell Douglas, Lockheed Martin, Boeing,

Raytheon, Northrop, Grumman, Rockwell) to make the fighters has dwindled to a select few (Boeing and Lockheed Martin). The current military aircraft inventory is aging with pilots forced to fly aircraft that were designed and often manufactured prior to their dates of birth. An aging aircraft inventory has increased sustainment costs as well as the military's overall level of readiness (Roche, 2002). Consequently, over the next few decades much of the military's aircraft will need to be replenished. Of great concern is that only a few companies remain capable of the design and manufacture of fighter aircraft. Therein, lies the dilemma for the U.S. government and ultimately, the country – with less of an industrial base, the necessary competition to ensure effective aircraft procurement will be much more difficult (Roche, 2002).

Aircraft procurement policies are now driven by funding constraints such as CAIV (cost as an independent variable) rather than by the existing enemy threat. In other words, the military will acquire the number of fighters that can be afforded given budgetary constraints rather than the number of fighters actually needed. This thesis argues that the performance or behavior of a manufacturing system is the direct result of the system's design or structure, which itself, is created and reinforced by the thinking espoused by company leadership. Thus, business results/objectives are the direct result of the system design – good or bad. Therefore, the number of Joint Strike Fighters and F-22's, for example, eventually procured by the U.S. military is really dependent on how well and how predictably Lockheed Martin can manufacture aircraft (Cochran, et. al, April 2002). The definition and importance of manufacturing system design is discussed in this thesis in sections 3 – 8.

1.2 Thesis Overview

This thesis is focused directed towards six primary objectives.

- To understand the 'thinking' and 'structure' that creates the physical system designs that Cochran defines as 'mass' - set forth in Chapter 3.
- To understand the 'thinking' and 'structure' that creates the physical system designs that Cochran defines as 'lean' - set forth in Chapter 4.
- To understand the design of a predictable manufacturing system as defined by the Product Delivery System – set forth in Chapter 5.
- To understand the impact of requirement achievement from the redesign of a real-life manufacturing cell – set forth in Chapter 6.

- To understand the development of an investment and resource allocation methodology to support manufacturing system design implementation – set forth in Chapter 7.
- To understand the application of the Logical System Design Model [Cochran, et. al, April 2002] in a major manufacturing company – set forth in Chapter 8.

Central to the development of this thesis is the idea that 'the thinking' creates the 'structure', which then drives the 'behavior' see Figure 1-2.

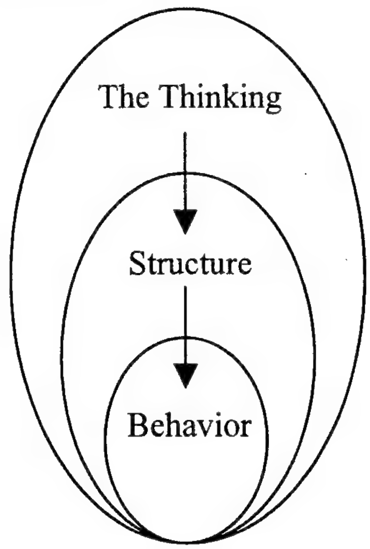


Figure 1-2 The Thinking, Structure and Behavior Framework [Cochran, et. al, April 2002]

In order to affect enduring change in a system, the thinking must first be altered. The idea is that there is a thinking-structure-behavior path-dependency necessary in order to initiate and sustain lasting changes in the system's design [Cochran, et. al, April 2002]. This framework will be used to communicate the thinking required to create structures or the design necessary within a company that will yield positive business results.

CHAPTER 2 A SYSTEM DESIGN FRAMEWORK

2.1 Systems

A system may be defined as a set of interrelated elements arranged to achieve a desired result collectively or holistically rather than independently [Cochran, et. al, April 2002]. Between the elements within a system are patterns of relationships, which affect the output of the system as a whole [Cochran, Won, 2002]. The interrelationships between system elements occur either by design or coincidence [Crawley, 2001]. Most systems are open systems, which have definite inputs and outputs and act on its inputs to produce a desired output [Parnaby, 1979]. Every system operates as an element of a larger system and is itself, composed of smaller systems [Crawley, 2001] (see Figure 2-1).

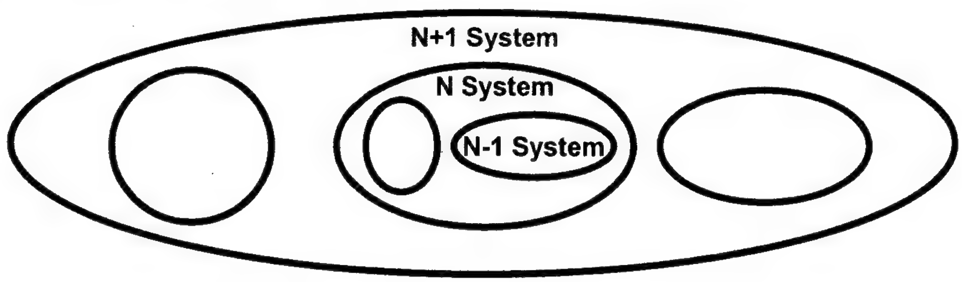


Figure 2-1 System of Systems

2.2 The Thinking, Structure and Behavior Framework

To minimize the complexity in the design and operation of systems, the following framework forms the basis for dialogue and change through the system design. The idea is that 'the thinking' creates the 'structure', which then drives the 'behavior' see Figure 2-2. In order to affect enduring change in a system, the thinking must be altered first. The idea is that there is a thinking-structure-behavior path-dependency necessary in order to initiate and sustain lasting changes in the system's behavior [Cochran, Won, 2002].

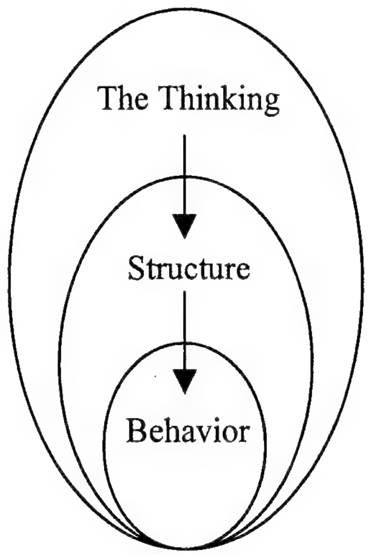


Figure 2-2 The Thinking, Structure and Behavior Framework

2.2.1 The Thinking

'Thinking' is defined as 'the way of reasoning; judgment; rational' [American Heritage, 2000]. How we think not only dictates how we make things but how we work, what we buy, and the way we live. Our thinking precedes everything we do. The same is true for societies, organizations and countries. Hence, Henry Ford statement rings true. "You can think you can or think you can't and you'll be right."

The discipline of working with mental models starts with turning the mirror inward; learning to unearth our internal pictures to the world, to bring them to the surface and hold them rigorously to scrutiny... and to the influence of others [Senge, 1994]. In response to the change needed in the approach to manufacturing, Hopp and Spearman claim, "In our view, the answer is not *what to do* about manufacturing problems but rather *how to think* about them [Hopp, Spearman, 1996].

2.2.2 The Structure

"The structure" in this framework may be interchanged with "logic" and "design." A comparison of their respective definitions sheds light on the thought that our behavior or actions emerge as a result of governing interpersonal and social structures [Cochran, Won, 2002]. 'Structure' is the interrelation or arrangement of parts in a complex entity. 'Logic' is the relationship between elements and between an element and the whole in a set of objects,

individuals, principles, or events. 'Design' is a basic scheme or pattern that affects and controls function or development [American Heritage, 2000].

Structure may also be synonymous with 'mental models' that are created and sustained by an organization's leadership [Cochran, et. al, April 2002]. Mental models may be defined as deeply ingrained assumptions, generalizations, or even pictures or images that influence how we understand the world and how we take action. Very often, we are not consciously aware of our mental models or the effects they have on our behavior. Mental models of what can or cannot be done in different management settings are no less deeply entrenched [Senge, 1994].

In human systems, structure includes how people make decisions – the "operating policies" whereby we translate perceptions, goals, rules, and norms into actions. Different people in the same structure tend to produce qualitatively similar results mainly because they were unable or unauthorized to alter the system or organization's design that caused the previous results. When there are problems, or performance fails to live up to what is intended, it is easy to find someone or something to blame. *But, more often that we realize systems cause their own crises, not external forces or individuals' mistakes* [Senge, 1994].

2.2.3 The Behavior

Often the behavior or the actions within a system represent the physical implementations – what is actually seen, the directly observable events and results [Cochran, Won, 2002]. As the framework indicates, enduring change can only be brought about by first, a change in the thinking and then the structure or design of the system. The phrase commonly used in hardware and software engineering is "the hardware is soft and the software is hard" [Boppe, 2001]. The same thought is true with respect to failed lean implementations. The physical tools of lean (i.e. kanban, kaizan, single-piece flow) are implemented because that is either all that the company knows or it is the easiest or least expensive thing to do. Quite often the results of such "lean" efforts are lower than expected and it is thought that Toyota or lean does not apply in our case. Ironically, the physical elements in a manufacturing system appear to be the most difficult to change, but actually the thinking and the structure is by far the most difficult and consequently where the largest potential gain lies for long-term system improvement.

The behavior, actions, performance, quality, cost and culture of a system or within an organization or company are all direct results of the system's design [Cochran, 1994]. Too often,

in order to meet Wall Street's profit expectations, executives will attempt to manage the numbers (i.e. profits, expenses,) instead of managing the means by which the numbers were created. Tom Johnson refers to these management styles as "management by means" and "management by numbers or objectives" [Johnson, Broms, 2000]. W. Edwards Deming, statistician and management innovator, said the following, "Focusing on outcome is not an effective way to improve a process or an activity... management by numerical goal is an attempt to manage without knowledge of what to do, and in fact is usually management by fear" [Deming, 2000]. "If management sets quantitative targets and makes people's jobs depend on meeting them, "they will likely meet the targets – even if they have to destroy the enterprise to do it" [Johnson, Broms, 2000]. Thus, positive, long-term behavior or results must be preceded by a change in the structure of the enterprise that can only come from a change in the thinking of company leadership regarding the design of the enterprise system.

2.3 Application of the Thinking, Structure and Behavior Framework to Two Ways of Thinking

Two main types of thinking prevalent in manufacturing system design today are "mass" thinking and "lean" thinking [Cochran, et. al, 2000] [Womack, 1990]. "Lean thinking" will hereafter be referred to as "systems thinking." The Thinking, Structure and Behavior Framework will provide a lens through which both types of thinking can be analyzed as to the resulting structures and behaviors. The effect of management accounting, scientific management and axiomatic design are identified as the dominant methods, which best link the respective thinking and the resulting system behavior.

CHAPTER 3 "MASS" THINKING

3.1 "Mass" Thinking Defined

It was not until the 17th century that people began to assume that they should separate objects from each other and systems into parts, specifically in order to quantify them, and also to control them. Today such thinking has become automatic [Johnson, Broms, 2000]. Organizational structures are perhaps the most visible effect of such thinking as enterprises or concretely divided up into marketing, procurement, quality, operations, etc. Each department often maximizes its own performance with respect to their individual responsibility with little visibility into the effect(s) on other departments. Such an approach results from a philosophy that assumes that the parts are not embodied in the whole and if the individual piece-parts are optimized, the whole is optimized (see Figure 3-1) [Cochran, Won, 2002]. This way of thinking finds its origins from the work of Frederick W. Taylor, the father of industrial engineering, and Sir Isaac Newton and the creation of Newtonian Physics [Johnson, Broms, 2000]. The core of Taylor's management philosophy consisted of breaking down the production process into its component parts and improving the efficiency of each part [Hopp, Spearman, 1996].

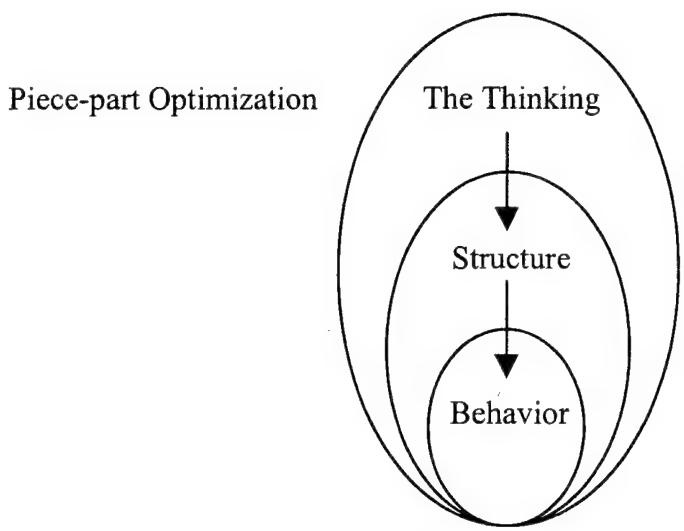


Figure 3-1 The Piece-part Optimization Thinking

Americans have always embraced the reductionist or analytical approach of science. The first unique American management system became known as scientific management. The reductionist method favored by scientists analyzes systems by breaking them down into their component parts and studying each one. This method was a fundamental tenet of scientific management, which worked to improve overall efficiency by decomposing work into specific

tasks and then improving the efficiency of each task. This approach is only acceptable if the improvements positively affect overall system performance and that of other parts of the system. The problem is that the reductionist and scientific management methods do not ensure that negative effects on the overall system are avoided. Today's industrial engineers and operations researchers still use this approach almost exclusively and are very much a product of the scientific management movement [Hopp, Spearman, 1996].

From a very early age, we are taught to break apart problems, to fragment the world. Sub-dividing tasks apparently makes complex tasks and subjects more manageable, but if done incorrectly, incurs a hidden, enormous price. For example, a procurement department, in order to maximize its performance, orders the minimum number of parts that does not account for fallout or variation in lead-time within a factory. Thus, procurement department expense is minimized but unquantifiable downtime on the factory floor in incurred. In larger organizations, the consequences of a specific department's actions are difficult to see and especially quantify; we lose our intrinsic sense of connection to a larger whole. When we then try to "see the big picture," we try to reassemble the fragments in our minds, to list and organize all the pieces. As physicist David Bohm says, the task is futile, similar to trying to reassemble the fragments of a broken mirror to see a true reflection. Thus, after a while we give up trying to see the whole altogether [Senge, 1994].

3.2 The Structures

3.2.1 Professional Management and Organizational Structure

"Increasingly after 1970, managers lacking in shop floor experience or in engineering training, often trained in graduate business schools, came to dominate American and European manufacturing establishments" [Johnson, Broms, 2000]. Reductionist and quantitative thinking began to shape management practices not only in large manufacturing firms, but also in business, governmental, and educational organizations all over the world. Financial statement metrics were used to drive work and to evaluate individuals at all levels in organizations. Johnson claims that instead of paying attention to how work is organized or designed and how the organization of work might affect financial results, managers increasing saw workers and organizations as collections of *objects*, responsive solely to pressure to achieve external quantitative targets. If cost objectives are not met, a primary means of reducing costs is to cut

jobs and/or close plants. Cost, however, is the result of the enterprise system design. Manipulating cost by cutting resources indiscriminately of the enterprise system design is nothing more than the tail wagging the dog, which results in other negative dynamics as future decrease in revenues, employee turnover, decreased revenues, employee work dissatisfaction, poor quality, etc. Johnson calls this belief of 'using quantitative measurement as the primary management tool' as "management by results" (MBR). MBR is perhaps the primary legacy of applying reductionist thinking to business practice. Not only did this management philosophy not reduce costs, it lead to rising costs and an accompanying decline in quality. Dr. W. Edwards Deming observed that such "managing by results" only makes things worse [Johnson, Broms, 2000]. He further states that if management sets quantitative targets and makes people's jobs depend on meeting them, "they will likely meet targets – even if they have to destroy the enterprise to do it." Such is the long-term effect of shortsighted actions resulting from the "management by the numbers" thinking [Johnson, Broms, 2000].

This proposed solution of the "professional manager" was evidenced at General Motors in the early 1900's. To resolve the problems associated with managing an enormous enterprise experienced by Henry Ford, Sloan created decentralized divisions managed objectively "by the numbers" from a small corporate headquarters [Womack, 1990]. Sloan thought it both unnecessary and inappropriate for senior managers at the corporate level to know much about the details of operating each division. If the numbers showed that performance was poor, it was time to change the general manager. General managers showing consistently good numbers were candidates for promotion to the vice-presidential level at headquarters [Womack, 1990].

Before WWII, it was traditional for managers to spend considerable time – a decade or more – in a job before being moved up the managerial ladder. After the war, however, there were simply not enough qualified people to fill the expanding need for managers. To fill the gap, business organizations identified rising stars and put them on fast tracks to executive levels. These individuals did shorter rotations through lower-level assignments – 2 or 3 yrs – on their way to upper-level positions. As a result, top manufacturing managers who came of age in the 1960s and 70s were likely to have substantially less depth of experience at the operating levels than their predecessors [Hopp, Spearman, 1996].

Worse yet, the concept of a fast track manager, first introduced to fill a genuine postwar need, gradually became institutionalized. Once some "stars" had moved up the promotion ladder

quickly, it became impossible to convince those who followed to return to the slower, traditional pace. A bright young manager who was not promoted quickly enough would look for opportunities elsewhere. Lifelong loyalty to a firm became a thing of the past in America, and it became commonplace for top managers in one industry to have come up the ranks of an entirely different one. American business schools preached the concept of the professional manager who could manage any firm regardless of the technological or customer details, and American industry practiced it. The days of Carnegie and Ford, owner-entrepreneur-managers who know the details of their businesses from the bottom up, were gone [Hopp, Spearman, 1996].

The compartmentalization of the professional labor spread into new professions of financial managers and marketing specialists to complement the engineering professions. Such compartmentalization took top management out of the loop with respect to operations and caused responsibility to devolve to middle management, who lacked the perspective to see operations management in its strategic context. As a result, middle managers and the academic research community that supported them approached operations from an extremely narrow, reductionist perspective [Hopp, Spearman, 1996]. Eventually, every functional area of the firm now had its dedicated experts. The division of professional labor was complete – with little holistic, systems perspective [Womack, 1990]. By the end of WWI, scientific management had firmly taken hold, and the main pieces of the American system of manufacturing were in place. Large-scale vertically integrated organizations making use of management accounting system production techniques were the norm [Hopp, Spearman, 1996].

3.2.2 Academic Structure

The first industrial engineering (IE) departments, like the early business schools, were heavily influenced by the scientific management movement [Hopp, Spearman, 1996]. The pure case study approach may be superior because cases can provide insights into realistic production problems. However, covering hundreds of cases in a short period of time, as is done in some of the best business schools, only serves to strengthen the notion that executive decisions can be made with little or no knowledge of the operational details. Moreover, unless there is some kind of integrating framework for the insights gleaned from the cases, it will be difficult to extend them into real and unique situations [Hopp, Spearman, 1996]. Such curriculums serve to strengthen and reinforce the academic and industry thinking and belief in the competency of the

"professional manager" who is able to successfully manage in any industry with only superficial knowledge of the operational details.

3.2.3 The Management Accounting Structure

3.2.3.1 The Logic Behind Management Accounting

One of the objectives of a management accounting system is to accurately calculate the costs of various products produced by a single enterprise. Accounting systems for managerial decisions and control can be traced back to the origins of hierarchical enterprises in the early nineteenth century [Johnson, Kaplan, 1987]. Management accounting was developed over a period from the 1890s to 1930s and has stayed relatively the same since its development. However, manufacturing techniques and practices have dramatically changed over the past 20 years [Cochran, 1994]. The existence of the management accounting structure within manufacturing is in the form of the unit cost equation (see Equation 3-1) [Cochran, et. al., April 2002 and Cochran, et al., 2000].

$$\text{MIN TC} = \sum_{i=1}^{n} \text{Min Unit Cost } (Op_i)$$

where n = number of operations

Equation 3-1 Unit Cost Equation

Application of management accounting to "control" the design and operations of a manufacturing system is a direct result of the 'mass' way of thinking or reductionism (see Figure 3-2).

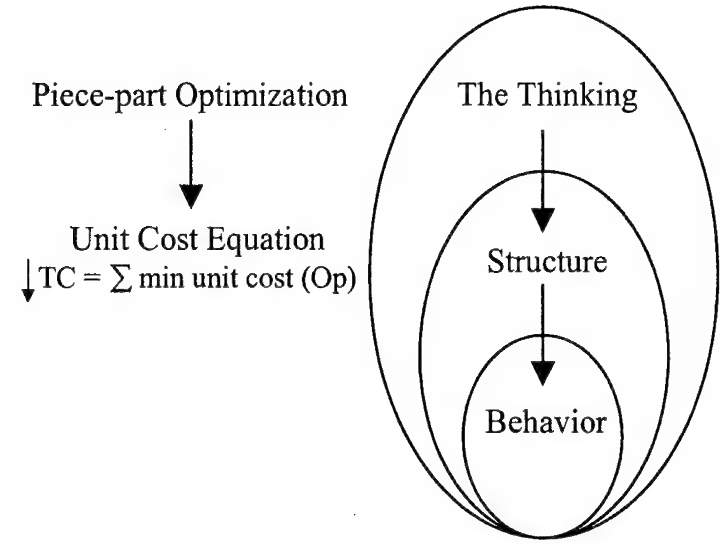


Figure 3-2 The Unit Cost Equation Structure

Further expansion of this structure leads to a more concrete and applicable equation that is then applied to individual operations within in plant. In words, Equation 3-2 says, "the unit cost is a function of the sum of the direct labor cost (DL), material cost (MTL) and the cost of overhead (OVHD), divided by the number of parts produced (n)" [Cochran, et. al., April 2002 and Cochran, et al., 2000].

$$\text{Unit Cost} = \frac{\text{DL} + \text{MTL} + \text{OVHD}}{\text{n}}$$

$$\text{...where OVHD} = \frac{\text{DL Hours } (\text{Op}_i)}{\text{Total Hours}}$$

Equation 3-2 Allocation of Overhead

Two fundamental flaws are inherent in Equation 3-2. The first assumption is that overhead cost within a factory can accurately be allocated based on the direct labor hours required to build a certain product. For example, in traditional manufacturing plants, the actual direct labor content of a production step is measured and overhead is apportioned to the direct labor content at the operation. The problem that exists is that over time, direct labor has become a small portion of the total cost, yet the traditional accounting measures, which have been synonymous with performance measures, force management to concentrate on direct labor cost reduction as a means to reduce total cost. In reality, materials cost and overhead are the pre-dominant cost today [Cochran, 1994]. The second flaw inherent in Equation 3-2 is that cost is

viewed at the operation level (i.e. does not view cost as the *result* of the work done to achieve the requirements of a system design [Cochran, April 2002 and Cochran, et al., 2000].

3.2.3.2 The Application of Control System Theory

To assess and better understand why the application of the unit cost equation creates an uncontrollable system, control theory will be applied since the unit cost equation is used for control purposes within a factory. The fundamental principle of control theory is to determine the error or difference between a desired result and the actual outcome. For this result to happen, the actual outcome must be measured. A control system seeks to match the output (the result) to the desired "set-point level." The ability of a system to control itself relies on its ability to respond to changes in the inputs and compensate for external and internal influences to the system that affect the objective function. Kuo states that, "the objective of the control system is to control the outputs in some manner prescribed by the inputs through the elements under control" [adapted from Kuo, 1991]. Figure 1-2 illustrates the control model, which has traditionally been applied to process control [Cochran, 1994].

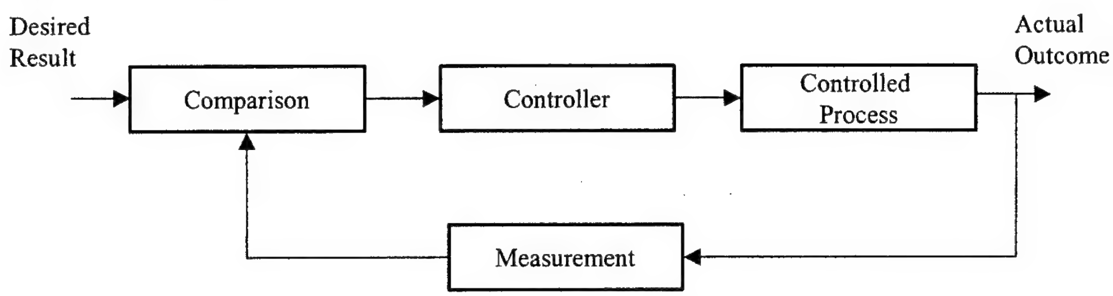


Figure 3-3 Standard Closed Loop Control Model

Three basic requirements (R) and solutions (S) of the control model above are:

R1 – Acquire & sort data	S1 – Measurement (PM)
R2 – Immediately flow and direct information	S2 – Comparison
R3 – Control the system	S3 – Controller

From an axiomatic design perspective (see section 4.2.3), the above requirements and solutions form a path-dependent design, which is an acceptable design with respect to the independence axiom (see Figure 3-4).

$$\begin{bmatrix} X & - & - \\ X & X & - \\ X & X & X \end{bmatrix}$$

Figure 3-4 Design Matrix

3.2.3.3 Acquiring Data - Measurement

The underlying assumption of system control theory is that what is being measured, if controlled accordingly, will return the system to the desired result or output. The problem is that the management accounting is now measuring the wrong items in the wrong way [Cochran, 1994]. Financial managers, relying exclusively on periodic financial statements for their view of the firm, become isolated from the real value-creating operations of the organization and fail to recognize when the accounting numbers are no longer providing relevant or appropriate measures of the organization's operations [Johnson, Kaplan, 1987]. Without the recognition that customer satisfaction, quality, variety and on-time delivery are important customer wants, many American industries still follow the paradigm of making direct labor hours and machine utilization the key measurables of productivity. Still worse is that the Generally Accepted Accounting Principles prescribe the use of direct labor hours as the foundation for manufacturing cost measurement [Cochran, 1994].

As Maskell has pointed out, the problem with traditional management accounting is that the accounting information is often irrelevant to the manufacturing strategy or functional requirements of the manufacturing system. Management accounting distorts manufacturing costs by assuming inaccurate cost patterns and apportions overhead incorrectly [Maskell, 1991]. Everyone is subjected to the needs of the financial accounting system and may perform counterproductively to the needs of the manufacturing system, as a result. Instead of cost alone, emphasis should be placed on the functional requirements of the manufacturing system design [Cochran, 1994].

American management assumes that "management by the numbers" can somehow attain operational stability. Measurement of the system output is viewed as the key control variable to achieving business success. Cost is not viewed as a result, but is considered a variable that can be controlled with the hiring and firing of employees to meet Wall Street's short-term targets. The truth is that most activities on the factory floor cannot be measured with any degree of

accuracy and the higher the level of aggregation of the data, the more inaccurate the data becomes. Dr. W. Edwards Deming stated that although we can only quantify 3% of all that is going on in an organization, management seems to devote 97% of its time to that measurement effort [Johnson, Brom, 2000].

3.2.3.4 Immediate Feedback of Information

With respect to the control model in Figure 3-3, the second requirement (R2) "*Immediately* flow and direct information" is also not satisfied by the application of management accounting system to control a manufacturing system. Management accounting systems are not providing useful, timely information for the process control, product costing, and performance evaluation activities of managers [Johnson, Kaplan, 1987].

Today's management accounting system is too late (time), too aggregated (generic or high level), and too distorted (wrong) to be relevant for managers' planning and control decisions. With respect to computing a monthly or quarterly income figure, the figure does not measure the actual increase or decrease in economic value that has occurred during the period [Johnson, Kaplan, 1987].

Fast feedback is an attribute of an appropriate performance measure. Traditional measures report that a problem has occurred after it is too late to do anything about the problem. For example, the cost accounting reports are available weekly or monthly and show the variances in material costs, material usage, labor productivity, labor rates, over allocation and others. When the recipients read any of these cost accounting reports, little can be done about the problem. Either the problem had occurred so long ago that it is impossible to investigate the cause, or the problem had already been identified and corrected by other means. Traditional performance measures are based on the concept of monitoring people's work so that they can be assessed, rather than providing the information that will *help* them to improve [Cochran, 1994].

3.3 The Behavior

People are motivated to take the wrong actions because they are seeking to achieve the irrelevant targets prescribed by the management accounting system [Cochran, 1994].
There are two types of measurables: financial measurables, which are used for financial reporting to the stockholders and performance measurables, which gauge the health of manufacturing

operations. Performance measurement and financial reporting must no longer be thought of synonymously. Maskell points out that financial reporting should not be the only basis for performance measurement [Cochran, 1994].

> The fundamental flaw in the use of management accounting reports for operational performance measurement is the assumption that financial reports are valid and relevant to the control of daily business operations. This assumption is wrong. Not only are financial reports irrelevant to daily operations, they are generally confusing, misleading, and is some cases positively harmful to the business… the day-to-day control of manufacturing and distribution operations is handled better with non-financial (performance) measures [Maskell, 1991].

The American system evaluates the system design (if at all) in terms of direct labor elimination (whether or not it is value-added or the most cost effective) and does not pay due diligence to the elimination of non-value added operations or activities (such as transport, and material handling). In fact, American engineering is forced to concentrate on improving the opposite of what should be improved due to improper and inadequate performance measures. Since the driving performance measurable is to reduce direct labor, many non-value-added operations are automated. Operations are automated at the expense of not increasing the effectiveness of the manufacturing system [Cochran, 1994].

Minimization of total cost must come as a result of system improvement instead of the summed improvement of individual operations. The four types of operations in a manufacturing system are processing, transport, storage and inspection. Two value streams are described in Figure 3-5 below [Cochran, et. al., April, 2002]. The lower value stream has been redesigned in order to achieve continuous flow of the product by eliminating the interim storage functions and most of the resulting transportation activities. Both have similar total costs based on the unit cost equation because the unit cost equation does not recognize many sources of cost and will only accept cost as long as it is minimized [Cochran, Won, 2002].

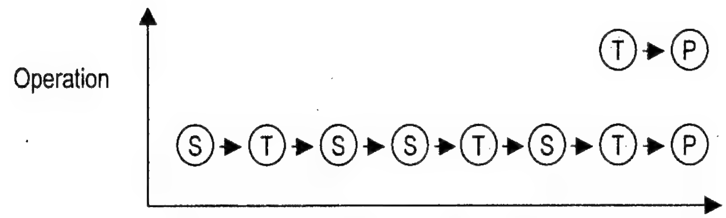


Figure 3-5 Operations Improvement vs. System Improvement

Due to the enforcement of the unit cost equation structure, Figure 3-6 depicts the following behaviors are consequently prevalent in many companies [Cochran, et. al., April, 2002].

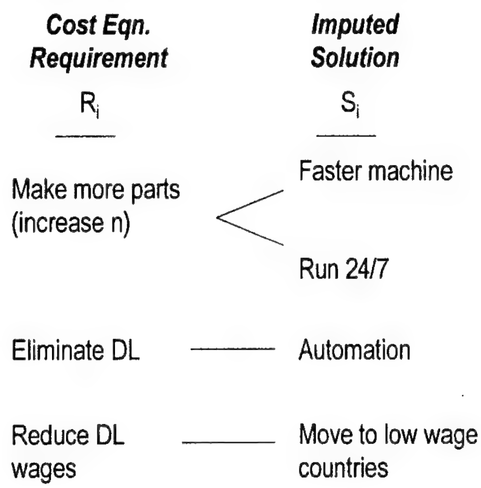


Figure 3-6 Resulting Behaviors from the Unit Cost Equation

The above actions in Figure 3-6, result in "mass manufacturing" (see Figure 3-7) [Cochran, Won, 2002].

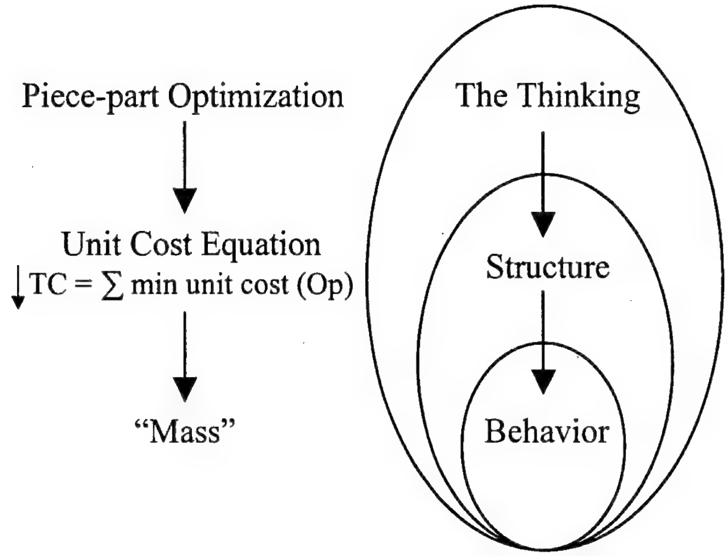


Figure 3-7 Mass Manufacturing – the Physical Result

Within the management accounting structure two main dynamics are experienced:

1. As direct labor (DL) decreases, indirect labor & investment increases;
2. The unit cost equation of management accounting attempts to *optimize* ineffective system designs. It does *not* reinforce putting in stable, cost-efficient, robust systems designs.

This resulting structure and its unintended results can be shown with the following system dynamics diagram (see Figure 3-8) [Cochran, et. al., April, 2002 and Cochran, et. al. 2000].

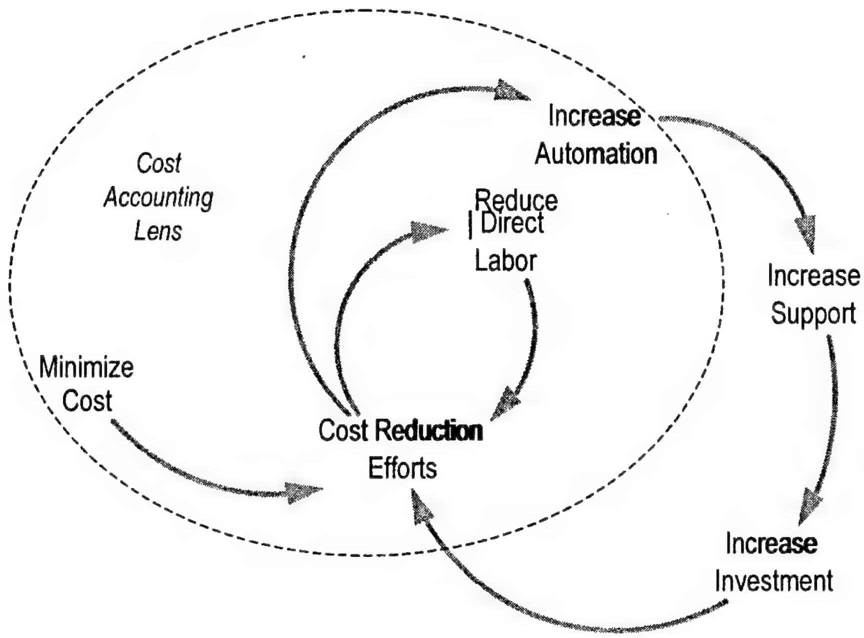


Figure 3-8 Unit Cost Equation Structure and the Unintended Results

In the past fifty years, most manufacturers who have strived to produce a larger product mix or variety have remained committed to the management accounting systems structure that says high profits depend, ultimately, on producing at low costs by running operations without interruption at full capacity for as long as possible. They apparently see no benefit to reducing the time it took to do individual changeovers. Instead, as they increased the variety of output, they took steps to reduce the total amount of time spent changing over. They did so by separating the various processes through which material flowed continuously in the early River Rouge plant. With processes separated, material for different varieties could be batched and processed "efficiently" in long runs that economized on changeovers [Johnson, Broms, 2000].

In the 1970's Taiichi Ohno commented on the importance of developing this capacity when he was asked to compare the system developed by Toyota after 1960 with the system developed after that date by the major American auto makers. Ohno said that the American understood the workflow established by Henry Ford at his River Rouge plant by the 1920s, but they failed to carry it to its logical conclusion. That conclusion, according to Ohno, was to extend the continuous workflow from the final assembly line to all other upstream processes. But while American producers maintain a continuous flow in final assembly, "they *force* the work to flow" in upstream areas. Consequently, "America's system of mass production," said

Ohno, "generates unnecessary losses in pursuit of quantity and speed" [Johnson, Broms, 2000]. Such management accounting systems were shunned by Taiichi Ohno, who is alleged to have said that he succeeded with the Toyota Production System only because Mr. Toyoda kept the cost accountants out of his hair [Johnson, Broms, 2000].

An ineffective management accounting system can undermine superior product development, process improvement, and marketing efforts. Where an ineffective management accounting system prevails, the best outcome occurs when managers understand the irrelevance of the system and by-pass it by developing personalized information systems. But managers unwittingly court trouble if they do not recognize an inadequate system and erroneously rely on it for managerial control information and product decisions [Johnson, Kaplan, 1987].

3.4 Conclusion – Poor Business Results from a Poor System Design

Long-term success of any system is a direct result of its system design. The system design that results in "mass manufacturing" is no different. For example, the following unit cost equation with the material cost, freight cost, direct labor cost, and overhead cost (allocated on the basis of direct labor) is considered (see Figure 3-9) [Cochran, et. al., April, 2002].

$$\text{MIN TC} = \sum_{i=1}^{n} \text{Min Unit Cost } (Op_i)$$

$$\text{Unit Cost}(Op_i) = \frac{{}^{\$}\text{MTL} + {}^{\$}\text{FRHT} + {}^{\$}\text{DL} + {}^{\$}\text{OVHD } (Op_i)}{n}$$

Figure 3-9 Example Unit Cost Equation

From the high-level requirement of "Minimize total cost" and its solution of "Produce at minimum unit cost," five lower level requirements can be derived (see Figure 3-10) [Cochran, et. al. 2000].

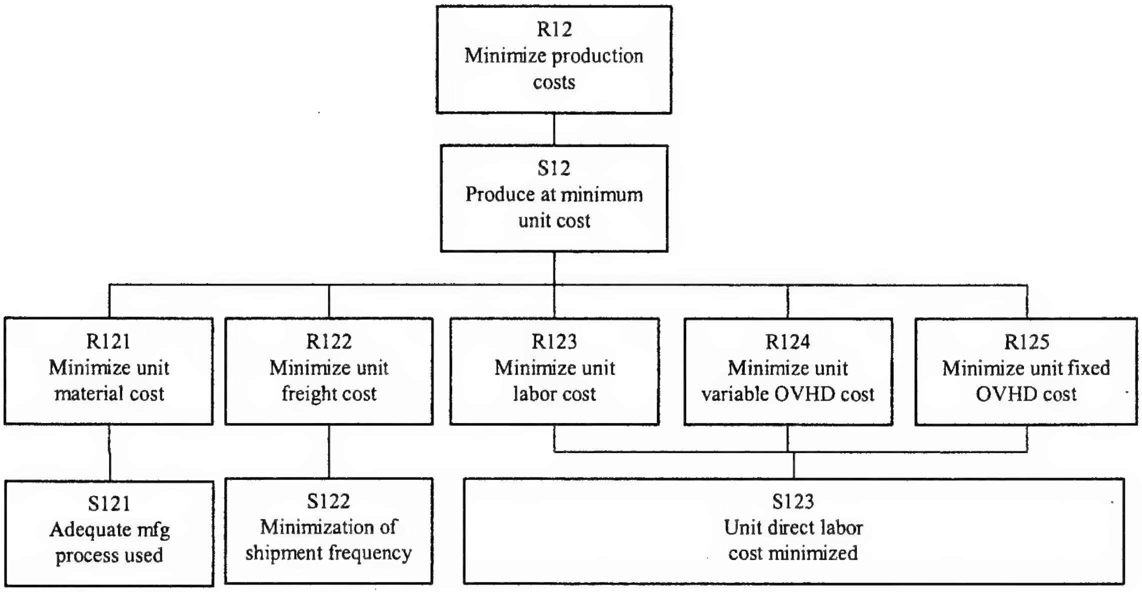


Figure 3-10 The System Design of the Unit Cost Equation

The resulting decomposition above results in a design equation with a fewer number of solutions than requirements (see Equation 3-1).

$$\begin{Bmatrix} R121 \\ R122 \\ R123 \\ R124 \\ R125 \end{Bmatrix} = \begin{bmatrix} X & - & - \\ - & X & - \\ - & - & X \\ - & - & X \\ - & - & X \end{bmatrix} * \begin{Bmatrix} S121 \\ S122 \\ S123 \end{Bmatrix}$$

Equation 3-3 Unit Cost Equation's Design Equation

The above equation (Equation 3-3) represents an incomplete design and created the following theorem regarding this general type of design.

<u>Theorem 1</u> Coupling Due to Insufficient Number of Solutions [Suh, 2001]

When the number of solutions is less than the number of requirements, either a coupled design results or the requirements cannot be satisfied.

Because this design violates the independence axiom, the design is considered unacceptable. Had axiomatic design been used prior to the application of the unit cost equation for control of the manufacturing system, the negative results and consequences of an unacceptable system design could have been predicted and the high system cost avoided [Cochran, et. al., April, 2002]. Implementation of the unit cost equation for control purposes

resulted in coupled manufacturing systems, characterized by a lack of robustness to internal and external operation variation. The lack of robustness led to inherent system instability, much higher manufacturing cost, poor quality and longer and more variable lead times to the customer.

CHAPTER 4 "SYSTEMS" THINKING

4.1 Systems Thinking Defined

In Chapter 2, a "system" was defined as a set of interrelated elements, which perform a function, whose functionality is greater than the sum of the parts [Crawley, 2001]. While "mass thinking" focused on the optimization of the elements within a system in isolation, "systems thinking" focuses not only on the performance of the elements, but especially their dependencies and influences on other system elements (see Figure 4-1).

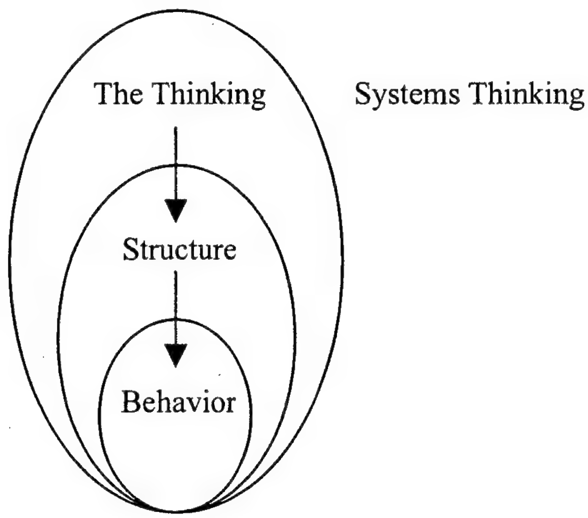


Figure 4-1 Systems Thinking

While no one, either in industry or academia, seems to disagree with "systems thinking," the challenge lies in how can an organization connects its thinking or sometimes popularly referred to in academia as "strategy" to the operational level or factory floor and vice versa while ensuring complete and proper (i.e. non-conflicting) alignment between the two. In a manufacturing context, this can be referred to as connecting the Big "M" (strategy) to the Little "M" (operations). One of the main problems in ensuring such alignment occurs because the enterprises strategy is set as the corporate level and operations occur many levels down the vertical organizational ladder, in multiple locations, and by many different people.

Complexity within a system is mainly dependent on the number and nature of the interrelationships between the system elements. The interrelationships between system elements occur either by design or coincidence [Crawley, 2001]. A scientific approach or methodology is paramount to ensure that an enterprises strategy or thinking culminates in operational excellence.

4.2 The Structure

4.2.1 System Design

Design involves the interplay between *what* we want to achieve and *how* we want to achieve it. This interplay (or mapping) is illustrated in Figure 4-2.

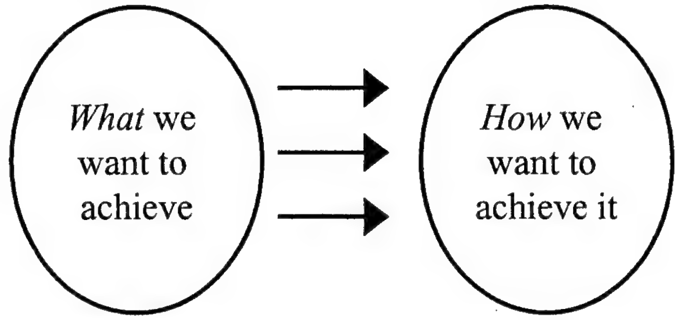


Figure 4-2 The Mapping Process of Design

Design is often associated with the word, "creativity." A subject is always mysterious when it relies on an implicit thought process that cannot be stated explicitly and explained for others to understand and that can be learned only through experience, apprenticeship, or trial-and-error. Such design approaches consistently yield a typical performance curve (see Figure 4-3), in which the last 10% of the project consumes cost and schedule and commonly forces reduced functionality or project scope.

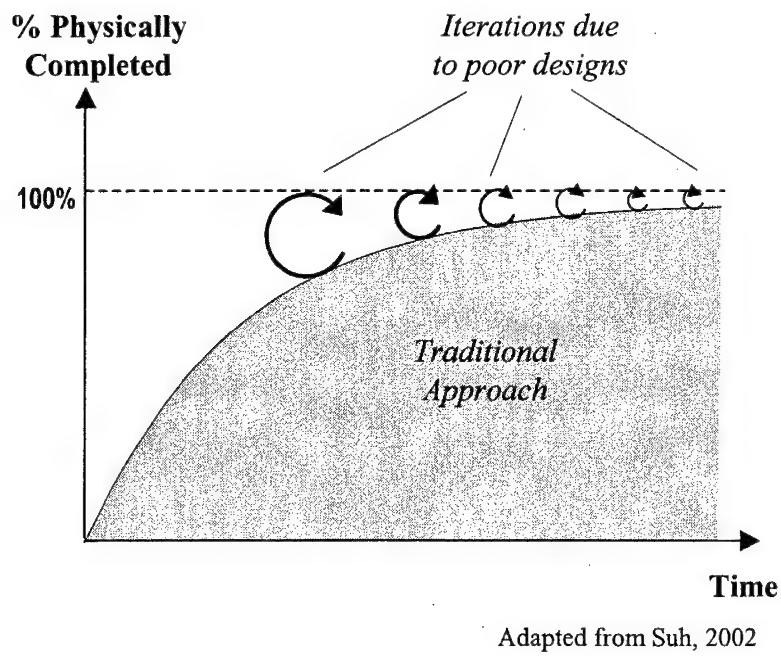


Figure 4-3 The Traditional Approach to Design

In many organizations, the prevailing culture accepts and justifies the time-consuming process described above (i.e. multiple iterations of "build-test-fix") as being the norm. In other words, they do not have time to design things correctly to begin with, but have plenty of time to fix past mistakes. Often the build-test-fix process is done under the rubric of optimization. Optimization of design typically involves coming up with the best compromise or design solution that compromises one of the original goals to satisfy another goal [Suh, 2001].

Academia abounds with current research on how to compress the engineering or design phase of a project and not surprisingly, terms for such efforts are heralded as "lean engineering." The problem is that nothing substantive is being changed to the design methodology itself to escape the "build-test-fix" problem that causes the development trend in the beginning. Albert Einstein stated, "We cannot solve our problems at the same level of thinking that created them" [Johnson, Broms, 2000].

Design has been one of these mysteries, but we must overcome this intellectual mental barrier. Design must become a principle-based subject. One of the greatest challenges of the design field is to overcome the acceptance of design as a subject in the arts rather than the arts and sciences [Suh, 2001]. Few people in academia have attempted to put a science behind the field of design and as a result, universities throughout the world have not given their engineering students generalized, codified, and systematic knowledge in design [Suh, 2001].

System design has lacked a formal theoretical framework and thus has been done heuristically or empirically (Rechtin, 1991). Heuristic approaches emphasize qualitative guidelines, exemplified by use of the phrases "Murphy's Laws," "make it simple," and "ask five why's." After systems are designed, they are sometimes modeled and simulated. In many cases, they have to be constructed and tested. All these very expensive and unpredictable processes are done to debug and improve the design after heuristic design solutions are implemented in hardware and software. Such an approach to system design entails both technical and business risks because of the uncertainties associated with the performance and the quality of a system that is created by means of empirical decisions [Suh, 2001].

Some people use dimensional analysis, decision theory, and other techniques to check or optimize a system that has already been designed. There are three issues with these approaches. First, such methods do not provide tools for coming up with a rational system design beginning from the definition of the design goals. Second, some of these methods simply confirm the result

to determine whether systems are correctly designed. Third, such methods are not general principles for system design because they cannot be applied to non-physical systems, such as software systems and organizations [Suh, 2001].

System design starts with defining the *logic* of the design with the idea that the logical design (i.e. the mapping between the *what* and the *how*) should drive the *physical* system design. The hypothesis of system design is that a system designer can define the pattern of relationships that will lead to predictable and stable results [Cochran, Won, 2002]. Defining the logical pattern of relationships of the system design requires defining the pattern of thought in the form of functional requirements and design parameters in advance of the physical design. This logical pattern of relationships, guided by axiomatic design principles, forms the structure that effectively connects systems thinking to the desired behavior or output of the system design [Cochran, Won, 2002].

4.2.3 Introduction to Axiomatic Design

Axiomatic design establishes a scientific basis for design and is based on two axioms, which differentiate between acceptable and unacceptable system designs. The Independence Axiom states that when there are two or more functional requirements, the design solutions must be chosen so that each functional requirement is satisfied in a predictable way. The Information Axiom states that the specified design solutions chosen should have the highest probability of requirement achievement [Suh, 2001].

Einstein describes the relevance of geometric axioms relative to the propositions [Einstein, 1961]. On the question that the propositions of Euclidean Geometry are true, Einstein says that,

> "Geometry sets out from certain conceptions such as "plane," "point," and "straight line, " with which we are able to associate more or less definite ideas, and from certain simple propositions (axioms) which, in virtue of these ideas, we are inclined to accept as "true." Then, on the basis of a logical process, the justification of which we feel ourselves compelled to admit, all remaining propositions are shown to follow from those axioms, i.e., they are proven. A proposition is then correct ("true") when is has been derived in the recognized

manner from the axioms. The question of the "truth" of the individual geometrical propositions is thus reduced to one of the "truth of the axioms."

The parallel to this line of thinking is that to question the "truth" of manufacturing system design and control propositions based on the axiomatic design approach is to question Suh's design axioms themselves [Cochran, 1994]. It is the application of axiomatic design to manufacturing system design and control that will enable the establishment of manufacturing system engineering as a science-driven field. When axiomatic design is applied, manufacturing system design and control will evolve as two pillars of manufacturing system engineering due to the establishment of a strong theoretical and scientific application base [Cochran, 1994].

Functional requirements (FRs) are defined as the minimum set of independent requirements that completely characterize the functional needs of the customer. Design parameters (DPs) are the key solutions that logically satisfy the specified set of FRs. The way in which the DPs affect the FRs determines whether the design is predictable and whether the independence axiom is satisfied [Cochran et. al, 2002]. This logical FR-DP mapping of axiomatic design provides the structure to bridge systems thinking to the desired system output (see Figure 4-4).

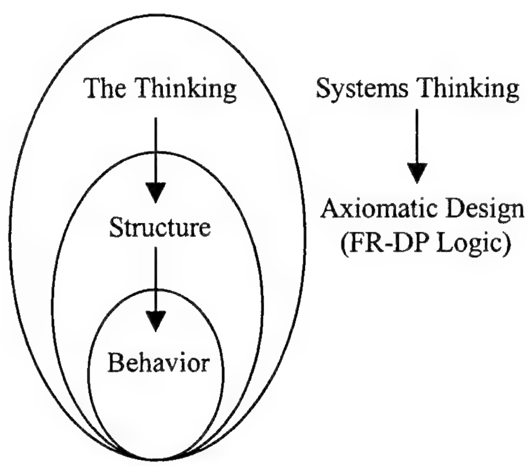


Figure 4-4 The Structure - Axiomatic Design's FR-DP Logic

Axiomatic design involves interplay between *what* we want to achieve (FRs) and *how* we choose to achieve it (DPs) (see Figure 4-5) [Suh, 2001]. Customers determine and drive the requirements. The success of any system design depends on satisfying the needs of the internal and external customer. System design takes these needs and translates them into system design requirements [Cochran, Won, 2002]. The effectivity of a system design first requires a definition

of the requirements before it is designed. This results in a clear definition of the objectives that the system design must accomplish [Cochran, 1994].

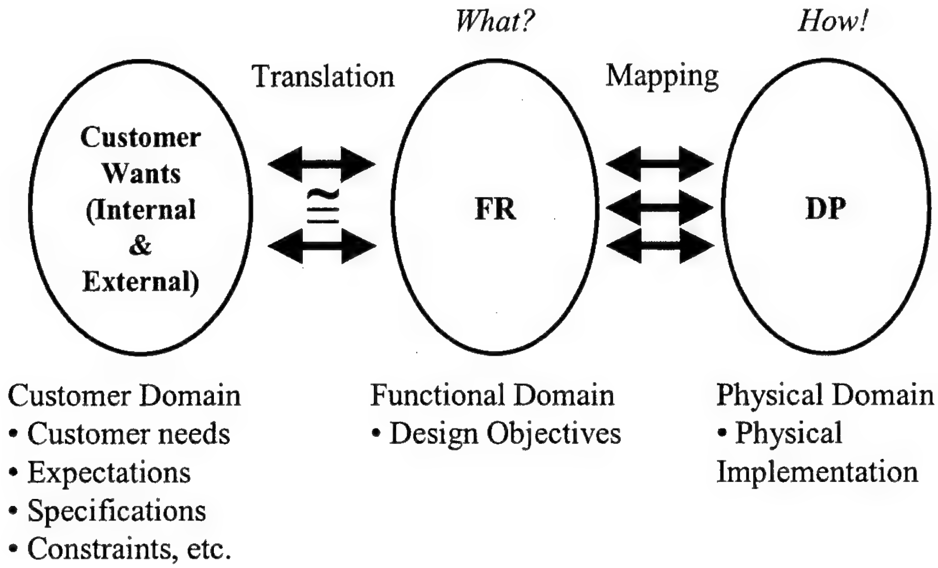


Figure 4-5 Three Domains of Design: Customer, Functional, and Physical

At a given level of a design hierarchy, the set of FRs that define the specific design goals constitutes the {FR} vector in the functional domain. Similarly, the set of DPs in the physical domain that has been chosen to satisfy the FRs constitutes the {DP} vector. The relationship between these two vectors can be written as:

$$\begin{Bmatrix} FR_1 \\ FR_2 \end{Bmatrix} = \begin{bmatrix} A_{11} & A_{12} \\ A_{21} & A_{22} \end{bmatrix} * \begin{Bmatrix} DP_1 \\ DP_2 \end{Bmatrix}$$

Equation 4-1 Design Matrix relating FRs to DPs

where [A] is called the design matrix. The design equation expresses the logical relationship between the FRs and the DPs. When Equation 3-1 is written in a differential form, the elements of the design matrix are given by:

$$A_{ij} = \frac{\partial FR_i}{\partial DP_j}$$

Equation 4-2 Differential Form of Design Matrix Elements [Suh, 2001]

4.2.3.1 Types of Designs

Axiomatic design identifies five main types of designs: uncoupled, path dependent (partially coupled), coupled, incomplete and redundant. To satisfy the Independence Axiom so that a design is predictable, the design must be either uncoupled or path dependent. An uncoupled design results when each FR can be satisfied independently by means of only one DP, resulting in a diagonal matrix (see Equation 4-3). This design is the best design and consequently, the most robust. In the design matrix an 'X' signifies that a DPj affects FRi. In this design, "tweaking" on lever DP2 only affects FR2.

$$\begin{Bmatrix} FR_1 \\ FR_2 \end{Bmatrix} = \begin{bmatrix} X & - \\ - & X \end{bmatrix} * \begin{Bmatrix} DP_1 \\ DP_2 \end{Bmatrix}$$

Equation 4-3 An Uncoupled Design

The second type of design is the path dependent design. This design results in a triangular matrix (see Equation 4-4) and the independence of FRs can be guaranteed if the DPs are implemented in the proper (path dependent) sequence. A path dependent design, while not ideal, is an acceptable design because it satisfies the independence axiom.

$$\begin{Bmatrix} FR_1 \\ FR_2 \end{Bmatrix} = \begin{bmatrix} X & - \\ X & X \end{bmatrix} * \begin{Bmatrix} DP_1 \\ DP_2 \end{Bmatrix}$$

Equation 4-4 A Path Dependent Design

Any other form of the design matrix having an equal number of FRs and DPs is called a full matrix and results in a coupled design (see Equation 4-5). A coupled design violates the independence axiom and has a low probability of FR achievement due to a high amount of information required to satisfy the requirements, especially in the presence of DP variation. Such designs often require the designer to repeatedly "tweak" the DPs in hope of achieving the FRs. Hence, coupled designs create an optimization problem [Suh, 2001]. In this design, tweaking on DP2 affects FR2 in a positive way and may affect FR1 in a negative way. This design is unacceptable because it violates the independence axiom.

$$\begin{Bmatrix} FR_1 \\ FR_2 \end{Bmatrix} = \begin{bmatrix} X & X \\ X & X \end{bmatrix} * \begin{Bmatrix} DP_1 \\ DP_2 \end{Bmatrix}$$

Equation 4-5 : A Coupled Design

The fourth design is an incomplete design, which is a design that has more FRs than DPs (see Equation 4-6). When the number of FRs exceeds the number of DPs, either a coupled design results or the requirements cannot be satisfied.

$$\begin{Bmatrix} FR_1 \\ FR_2 \end{Bmatrix} = \begin{bmatrix} X \\ X \end{bmatrix} * \begin{Bmatrix} DP_1 \\ - \end{Bmatrix}$$

Equation 4-6 An Incomplete Design

The last type of design is the redundant design, which is a design with more DPs than FRs (see Equation 4-7). A redundant design is a coupled design.

$$\begin{Bmatrix} FR_1 \\ - \end{Bmatrix} = \begin{bmatrix} X \\ X \end{bmatrix} * \begin{Bmatrix} DP_1 \\ DP_2 \end{Bmatrix}$$

Equation 4-7 A Redundant Design

Table 4-1 below summarizes the types of designs identified by axiomatic design.

Type of Design	Structure	Design Matrix	Comments	Behavior/Result
Uncoupled	FR_1 — DP_1 FR_2 — DP_2	$\begin{bmatrix} X & - \\ - & X \end{bmatrix}$	Independent (acceptable) design; ideal design; most robust; highest probability of FR achievement	Tweaking on DP_2 only affects FR_2.
Path Dependent	FR_1 DP_1 FR_2 DP_2	$\begin{bmatrix} X & - \\ X & X \end{bmatrix}$	Independent (acceptable) design;	Order of DP implementation is important;
Coupled	FR_1 DP_1 FR_2 DP_2	$\begin{bmatrix} X & X \\ X & X \end{bmatrix}$	Coupled (unacceptable) design; not robust; creates a system optimization problem;	Tweaking on DP_2 positively affects FR_2, but may negatively affect FR_1 – results in iteration
Incomplete	FR_1 — DP_1 FR_2	$\begin{bmatrix} X \\ X \end{bmatrix}$	Coupled (unacceptable) design; not robust	Either the design is coupled &/or all the FRs cannot be satisfied
Redundant	FR_1 — DP_1 DP_2	$\begin{bmatrix} X & X \end{bmatrix}$	Coupled (unacceptable) design; not robust	Either the design is coupled &/or all the FRs cannot be satisfied

Table 4-1 Types of Designs

4.2.3.2 Coupled Designs

Axiomatic design, synonymously referred to in this thesis as system design, provides a scientific methodology to manage the costs of complexity by avoiding complexity in the first place. Complexity is related to information content. The design that requires more information content is more complex [Suh, 2001]. The best design is the one that has the minimum information content because it has the highest probability of success [Suh, 2001]. "Based on years of experience of creating designs or analyzing designs, we have not come across a situation where a coupled design had lower information content that an uncoupled design" [Suh, 2001].

When the design matrix is a full matrix, a coupled design results. A coupled design may yield a unique solution that gives the right values for the FRs, but such a design generates many problems. For example, when one of the FRs is changed, all DPs must be changed. Also whenever the DPs are not exact and deviate from the desired (or set) values, the FRs may not be satisfied. Since most manufacturing processes cannot make exactly identical parts, the system or product may be individually tuned or calibrated. Furthermore, if one of DPs changes during the life of the product or process (say by wear), then the machine must be discarded unless all other DPs are changed accordingly" [Suh, 2001].

4.2.3.3 COMPLEXITY

The manufacturing field associates complexity with the amount of effort required to manufacture a product [Suh, 1990]. Even the simplest of products requires a significantly complex production system involving the interplay of many different disciplines within and organization. Suh defines two types if complexity:

1. **Real Complexity**

   Real complexity is related to information content, which is defined in terms of the probability of success of achieving the desired set of FRs. Real uncertainty exists even when the Independence Axiom is satisfied. Thus, real complexity may be reduced when the design is either uncoupled or decoupled, i.e., when the design satisfies the Independence Axiom.

2. **Imaginary Complexity**

   Imaginary complexity is defined as uncertainty that is not real uncertainty, but arises because of the designer's lack of knowledge and understanding of a specific design itself. Thus, imaginary complexity exists only in the mind of the designer. Even when the design is a good design, consistent with both the Independence Axiom and the Information Axiom, imaginary (or unreal) uncertainty exists when we are ignorant of what we have [Suh, 2001].

The role of the system designer is to resolve and/or minimize this complexity so as to create a manufacturing system can predictably meet all of its objectives in spite of internal and external operational variation.

4.3 The Behavior

4.3.1 Decreased Development Time and Cost while Increasing Functionality

Applying axiomatic design as the structure to connect systems thinking to the desired behavior breaks the paradigm of classical developmental timelines, previously referenced in section 4.2.1. In Figure 4-6 below, the development performance using axiomatic design is plotted on top of the traditional approach. Multiple "build-test-fix" iteration circles characterize the traditional approach and the developmental team has a false perception of the "percent completed." Tradeoffs are eventually inevitable as cost and schedule constraints force functionality to be de-scoped and the user invariably must wait for the next development program in hopes of gaining the originally desired functionality.

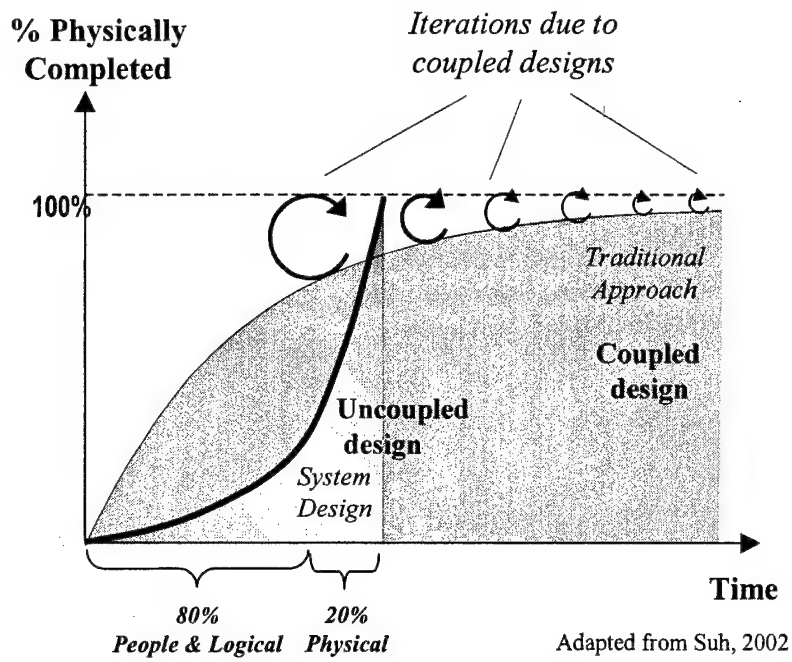


Figure 4-6 The Result of System Design

In comparison, the system design approach using uncoupled designs (functionally independent) greatly minimizes the non-value-added developmental activity of "build-test-fix." A key difference between the two methodologies is the amount of development time spent working on the logical structure (i.e. the FR-DP relationships) (approximately 80%) prior to building prototypes and working in the physical domain. For this structure or design methodology to be effective, the thinking of management and the customer must change. As seen in Figure 4-6, the resultant structure delivers all the functionality originally intended in less

time and at a lower cost. In the manufacturing industry, such a physical system is known as "lean" (see Figure 4-7).

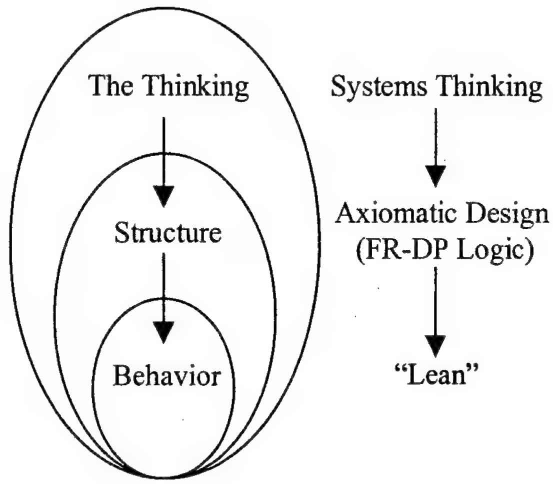


Figure 4-7 The Physical Result – "Lean"

4.3.2 Robust System Design

System robustness is the ability of a system to accommodate large variations in DPs and yet still satisfy the FRs [Suh, 2001]. Why is robust system design necessary? At the core of Dr. Deming's message is the assumption that variation in nature is normal [Johnson, Broms, 2000]. Therefore, systems must be designed to compensate for variation in the DPs and still consistently yield the desired output. Robust system design is a direct result of the independence axiom, which by definition means that a robust design has less information content, less complexity and thus, a higher probability of consistently satisfying the FRs. A system design that violates the independence axiom produces an unpredictable design, which either cannot satisfy the FRs or is not robust enough to fulfill the FRs at all times [Suh, 2001]. It is difficult to improve poorly designed systems. Coupled system designs cannot be made robust, built readily at low cost, and function reliably or as originally intended.

Systems that are designed to be robust are not only robust to internal and external (from suppliers) operation variation, but also to economic variation of the market. Southwest Airlines is an excellent example of a successful system design. Since their inception in 1973, the airline has made a profit every year [Freeburg, 1998]. Even in a highly variable industry, Southwest Airlines has made a consistent profit, even in 2001, when nearly all other airlines lost money due to the events on September 11th and the decline in air travel thereafter. Consequently, Southwest

Airlines has never laid off an employee due to poor financial profitability. Such results do not happen by accident; such companies are robust to market volatility because they have *designed* their systems to be flexible and robust.

4.3.3 System Stability

Variation is normal and results from changes in the DPs. Therefore, we must *design* the system to be robust [Cochran, 1994]. Such a system consistently yields stable output. W. Edwards Deming stated, 'Management objectives cannot be met by unstable systems' [Deming, 2000].

A system must be stable and controllable. If the system is not stable and changes randomly, it will not be reliable and controllable. If the system is not controllable, it cannot satisfy its functional requirements at all times. In this sense, it is argued qualitatively that when a system satisfies the Independence Axiom and the Information Axioms, the system is stable and controllable within its design range, because the DPs are chosen to satisfy each one of the FRs independently [Suh, 2001].

Dr. W. Edwards Deming in his book, *Out of the Crisis*, stated, "If you have a stable system, then there is no use to specify a goal. You will get whatever the system will deliver. A goal beyond the capability of the system will not be reached. If you have not a stable system, then there is … no point in setting a goal. There is no way to know what the system will produce: it has no capability" [Johnson, Broms, 2000]. Therefore, the first objective of any system is to attain system stability.

4.3 Conclusion - Two Ways of Thinking Compared

Figure 4-8 below represents the translation of the thinking into a structure that dictates the physical result. "Mass" and "lean", just like culture, cost and business profitability are only the results or behaviors of the system design.

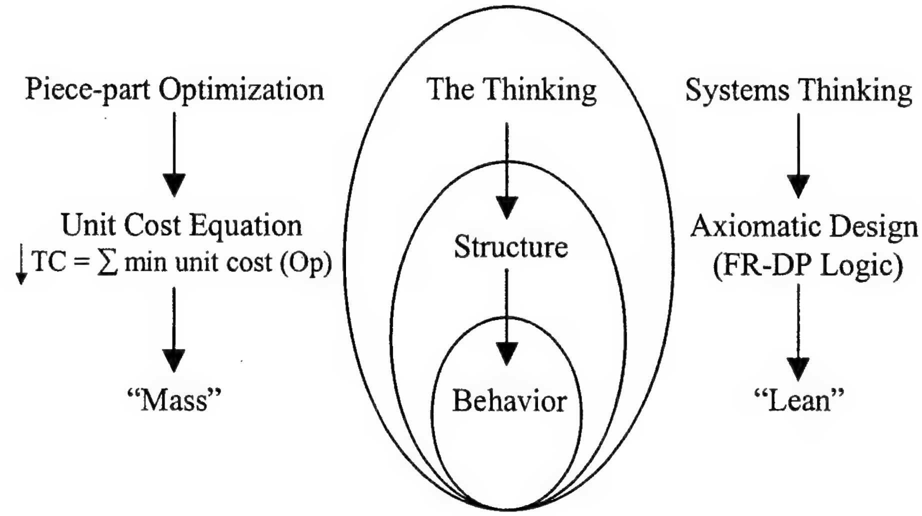


Figure 4-8 Two Ways of Thinking Compared

In "mass," the cost equation drove the physical design or implementation, but in "lean" the functional requirements come form the internal (employees) and external customers (people who purchase products).

Figure 4-9 below depicts the financial results of two businesses over time. Company A experiences increasingly variable earnings due to a lack of a robust system design, whereas Company B's system design experiences consistent profits year after year [Johnson, Broms, 2000].

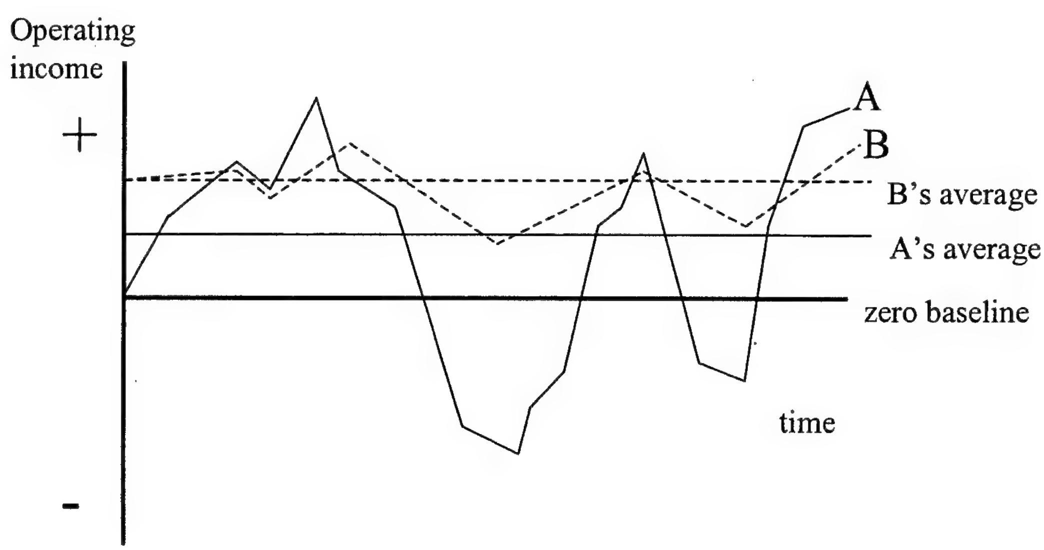


Figure 4-9 Robust System Design Stabilizes and Increases Financial Performance

System Design Implementation in the Aircraft Manufacturing Industry

Robust system designs not only will assure the long-term health and viability of organizations, it may also dampen and mitigate the eventual impact of future economic downturns [Johnson, Broms, 2000]. Flexibility in manufacturing will increase profits in a slow growing economy because the paradigm of management accounting systems production has bee re-written by system design: no longer is unit cost reduction proportional to the number of units produced [Cochran, 1994].

CHAPTER 5 THE PRODUCT DELIVERY SYSTEM

5.1 Manufacturing Systems

A manufacturing system is the arrangement and operation of elements (machines, tools, material, people, and information) to produce a value-added physical, informational or service product whose success and cost is characterized by measurable parameters of the system design [Cochran, 1994] [Chryssolouris, 1992] [Wu, 1992]. A manufacturing system is a subset of the production or enterprise system [Black, 1991]. The production system consists of all enterprise activities that support the manufacturing system (e.g., sales, marketing, distribution, product engineering) [Cochran, 1994]. People are an integral part of a manufacturing system and a main determining factor in the outcome of the system. Consequently, consideration of the "human aspect" in any manufacturing system is paramount.

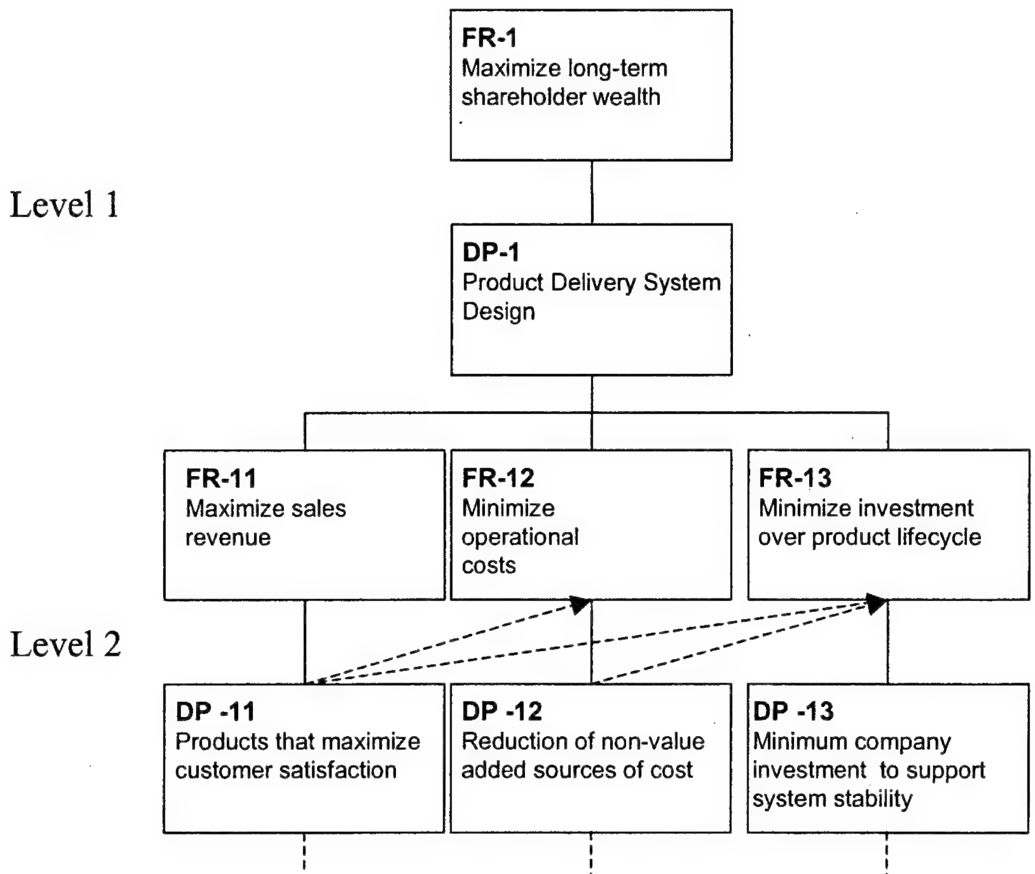
5.2 The Product Delivery System

Professor Cochran and his group at MIT have used axiomatic design to create a framework called the Product Delivery System (PDS), which represents the *design* for a stable manufacturing system that operates with the fewest resources [Cochran, 2000]. The PDS is applicable to a wide range of repetitive, discrete part manufacturing environments. The PDS attempts to achieve the following main objectives:

1. To clearly separate requirements for the means of achievement
2. To relate high-level company goals and requirement to low-level (operational) activities and decisions, thus allowing designers to understand how the selection of manufacturing solutions impacts the achievement of the requirements of the manufacturing system.
3. To portray and limit the interactions among different elements of a system design.
4. To effectively provide and communicate a mental model of the manufacturing system design (FR-DP logic) for an organization, so that system designers have a roadmap to achieve the "strategic" objectives of an organization [Hayes and Wheelwright, 1984].

The PDS is a path dependent (lower-triangular) design and clearly illustrates the importance of path dependency in manufacturing system design. Path dependency indicates that an FR is a function of multiple DPs. The high level branches of the PDS are path dependent (see Figure 5-1) [Cochran et. al, 2000]. The PDS consists of seven hierarchical levels of

decomposition. The highest-level functional requirement in the PDS and overall goal of a manufacturing system is FR-1 "Maximize long-term shareholder wealth" with the associated design parameter, DP-1 "Product Delivery System Design." This FR-DP pair is further decomposed into the following second level requirements derived from the return on investment formula: FR-11 "Maximize sales revenue", FR-12 "Minimize operational costs", FR-13 "Minimize investment over product life cycle" with the associated DP-11 "Products that maximize customer satisfaction", DP-12 "Reduction of non-value adding sources of cost", and DP-13 "Minimum company investment to support system stability", respectively (see Figure 5-1).



Design Equation
$$\begin{Bmatrix} FR-11 \\ FR-12 \\ FR-13 \end{Bmatrix} = \begin{bmatrix} X & 0 & 0 \\ X & X & 0 \\ X & X & X \end{bmatrix} \bullet \begin{Bmatrix} DP-11 \\ DP-12 \\ DP-13 \end{Bmatrix}$$

Figure 5-1 First Two Levels of the PDS and Design Equation

Level 2 FR-DP pairs are further mapped into the seven main branches if the PDS: product design, quality, identifying and resolving problems, predictable output, delay reduction, operational costs, and investment (see Figure 5-2). The complete version of the PDS is shown in Appendix A: The Product Delivery System (PDS). The logical FR-DP structure of the branches is a lower-triangular (path dependent) design. Because the PDS is a path dependent design, it satisfies the independence axiom of axiomatic design and thus, is an acceptable design. Figure 5-2 also demonstrates the path dependent approach of manufacturing system design with respect to the reduction of operation variation. Operation variation is defined as the throughput time variation (σ_{TT}), average throughput time variation [X(bar)$_{TT}$], process variation (σ_P) and the average process variation [X(bar)$_P$]. The path dependency (left-to-right direction of influence in the PDS) indicates that for the average variation of process or throughput to be effectively reduced, its degree of variability must first be reduced.

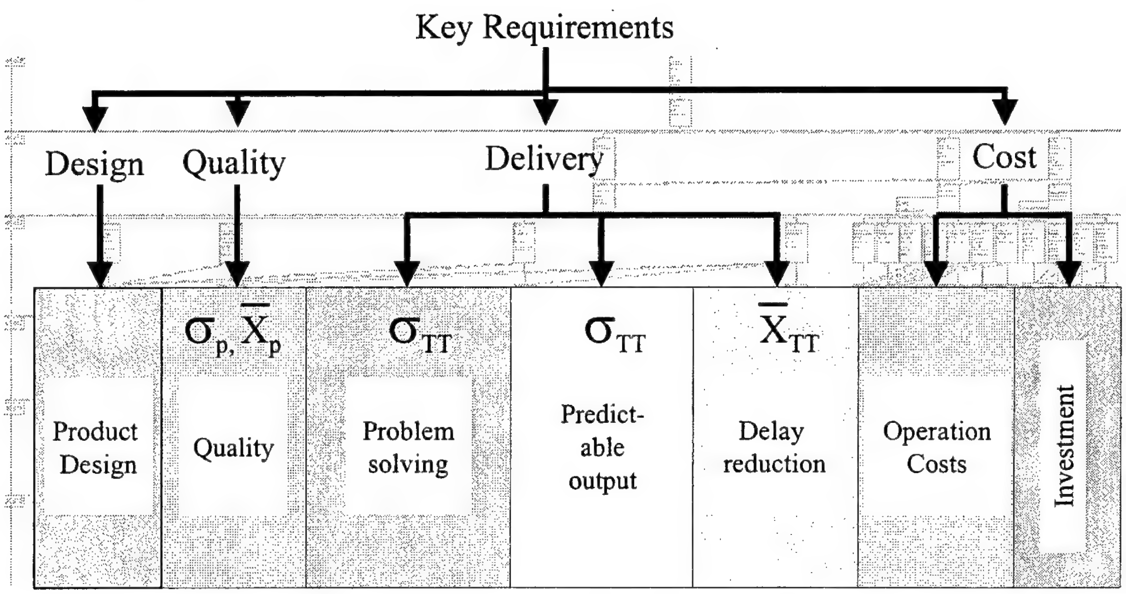


Figure 5-2 The Seven Branches of the Product Delivery System

5.2.1 The PDS and the Requirements of the Customer

A manufacturing system has two main classifications of customers, internal (employees) and external (those persons who purchase products). Both sets of customers impose unique sets of requirements on the manufacturing system design. For a manufacturing company to attain long-term profitability, all the requirements of all the customers (internal and external) must be

fully satisfied. Therefore, the system design process must begin with the customer (see Figure 5-3) [Cochran, et. al., April, 2002].

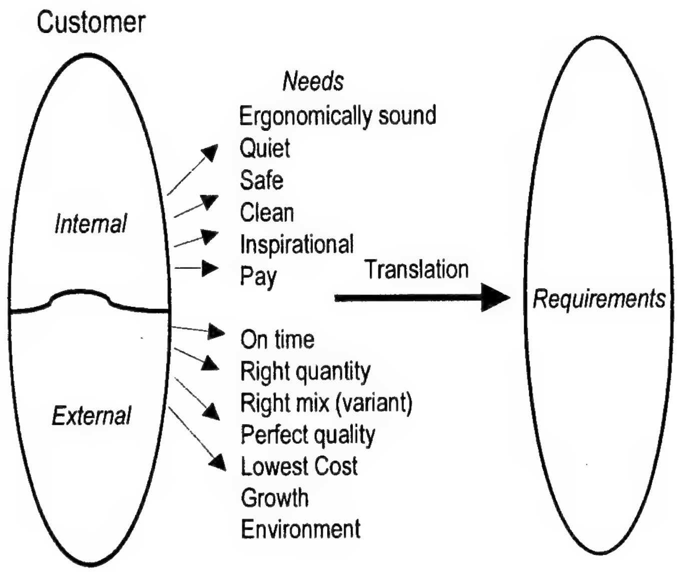


Figure 5-3 Translation of Customer Requirements

5.2.2 System Stability & the PDS

The PDS represents a system design in its entirety. *Every* FR must be achieved for the design to be complete. W. Edwards Deming, stated, 'Management objectives cannot be met by unstable systems' [Deming, 2000]. Professor Cochran defines the six requirements (R) for system stability as:

1. Provide a safe, clean, quiet, bright and ergonomically sound environment.
2. Produce the customer-consumed quantity every shift (time interval).
3. Produce the customer-consumed mix every shift (time interval).
4. Deliver perfect-quality products to the customer every shift (time interval).
5. Do R2 – R4 in spite of operation variation.
6. When a problem occurs in accomplishing R2 – R4, identify the problem condition immediately and respond in a standardized (pre-defined) way.

These attributes for a successful manufacturing system are discussed in a variety of writings [Cochran et. al, 2000] [Monden, 1998] [Schonberger, 1996] [Spear, 1999]. The six requirements for system stability are derived from the needs of the customer (see Figure 5-4).

For a predictable, effective design, the system designer logically defines the solutions (S) (i.e. the design parameters), S1 – S6, prior to physical implementation [Cochran, Won, 2002]. Without first logically designing the global system structure, local improvements become nothing more than ineffective local optimizations [Cochran, Won, 2002].

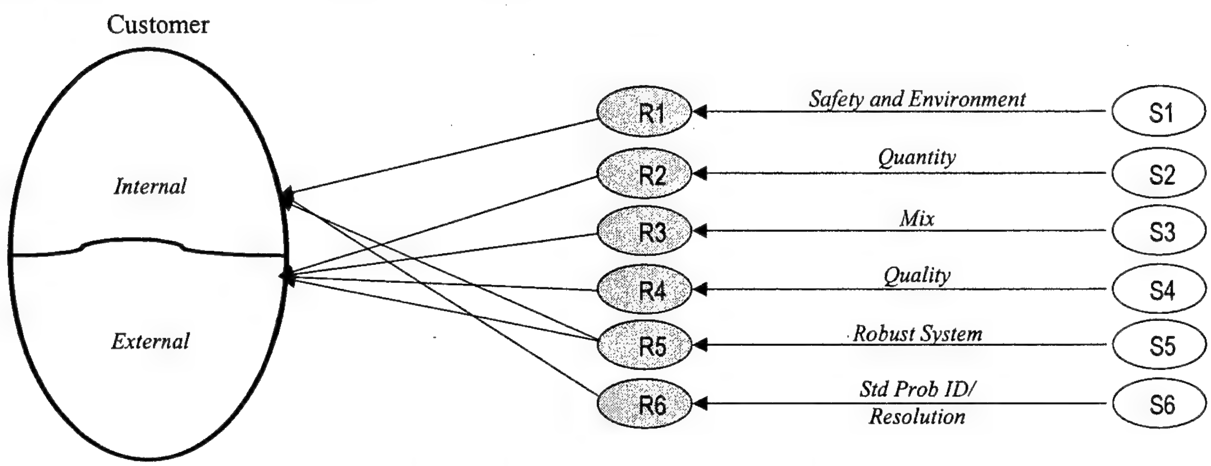


Figure 5-4 The Six System Stability Requirements of the Customer

The PDS (see Figure 5-5) incorporates the six requirements for system stability [Won et. al, 2001].

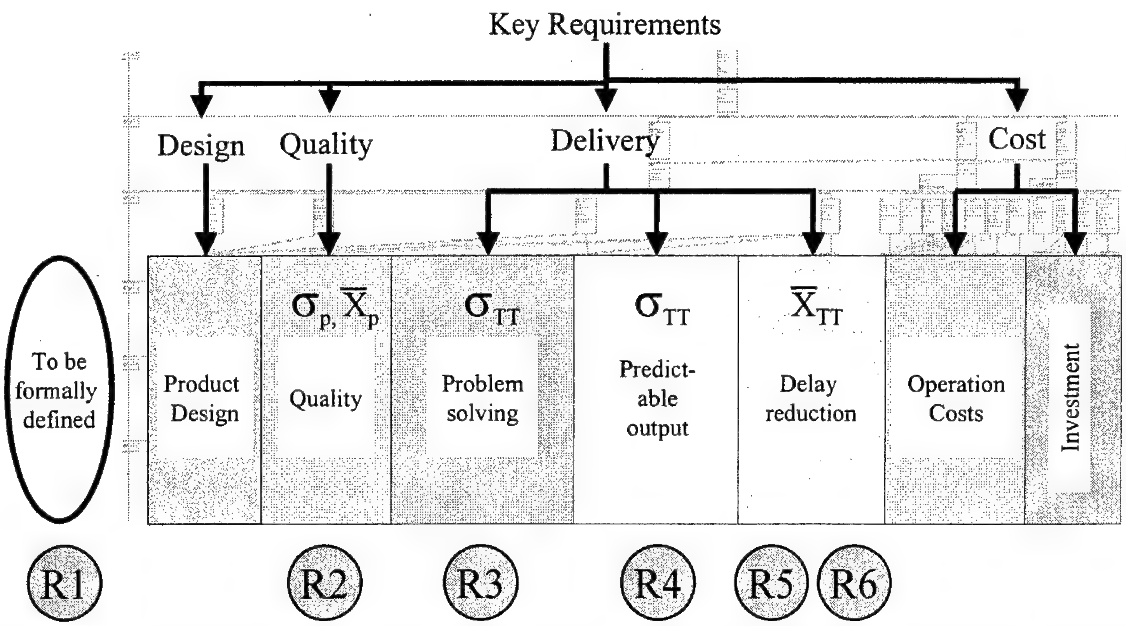


Figure 5-5 Product Delivery System (PDS) and the Six Requirements for System Stability

Cost is the direct result of the system design [Cochran, 1994]. Only when the manufacturing system is stable can waste be permanently reduced. When true waste is reduced, true cost is reduced [Cochran et. al, 2000] [Johnson, Broms, 2000] [Cochran, 1999]. The basic philosophy for achieving system stability and thus reducing cost is known as the "two-sided coin" (see Figure 5-6) [Cochran, Won, 2002].

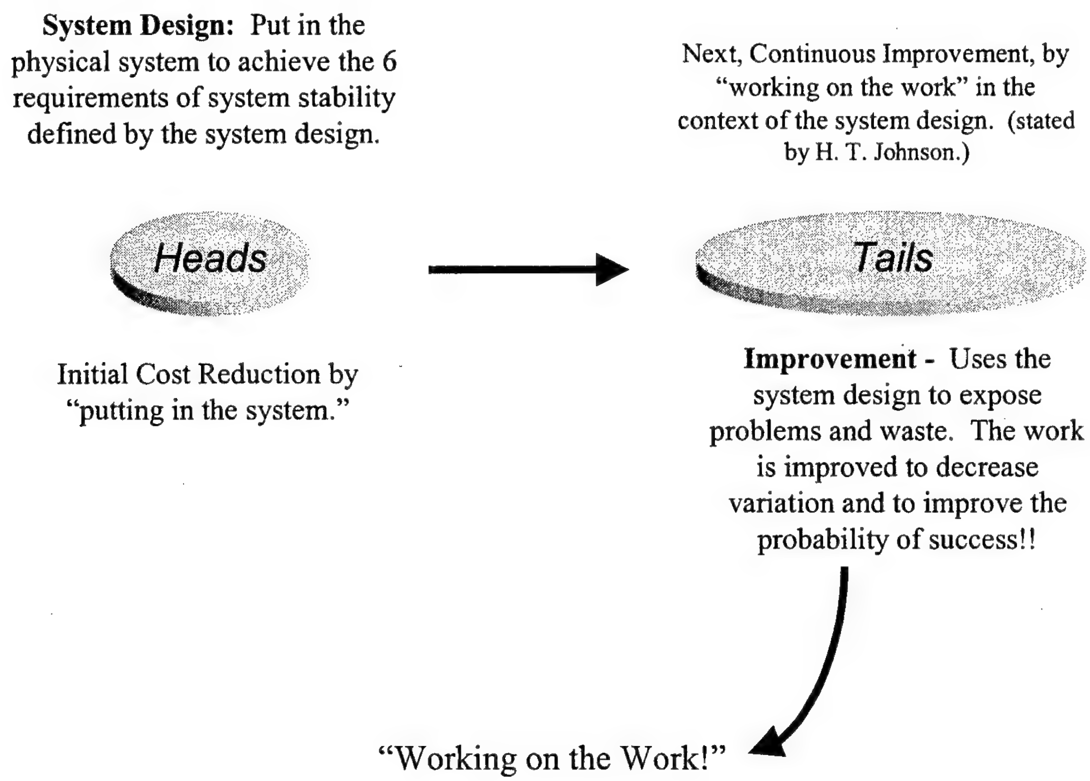


Figure 5-6 The Two-Sided Coin of Cost Reduction

5.2.3 Manufacturing System Design Evaluation

The 'health' of an existing manufacturing system design can be evaluated with a questionnaire based on the PDS [Linck, 2001]. The PDS questionnaire establishes standard criteria for a good production system design. The questionnaire contains specific questions about the leaf-level (lowest level) FR-DP pairs stated in the PDS. The questions use a five-point Likert scale to ascertain the level or degree of FR achievement of the system design as defined by the PDS. Questions are answered with one of the following choices: (1) strongly disagree, (2) disagree, (3) neither agree nor disagree, (4) agree, (5) strongly agree, and (0) not applicable. Open-ended questions force the respondent to answer in his own words and can lead to a deeper coverage of the system. Below is an excerpt from the PDS questionnaire's questions with

respect to the evaluation of FR-Q112 "Ensure that operator consistently performs tasks correctly" (see Figure 5-7).

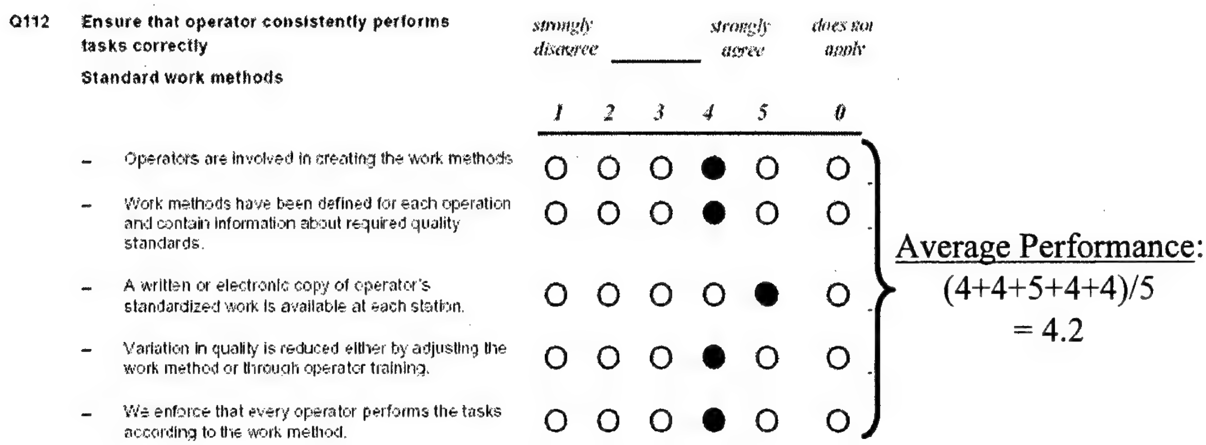


Figure 5-7 Illustration of Performance Calculation

Each leaf-level FR-DP pair of the PDS receives an average score based on the following performance scale (see Figure 5-8).

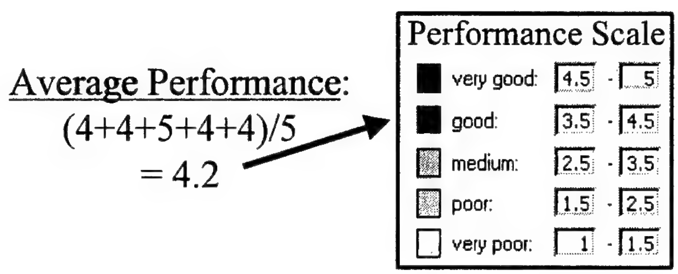
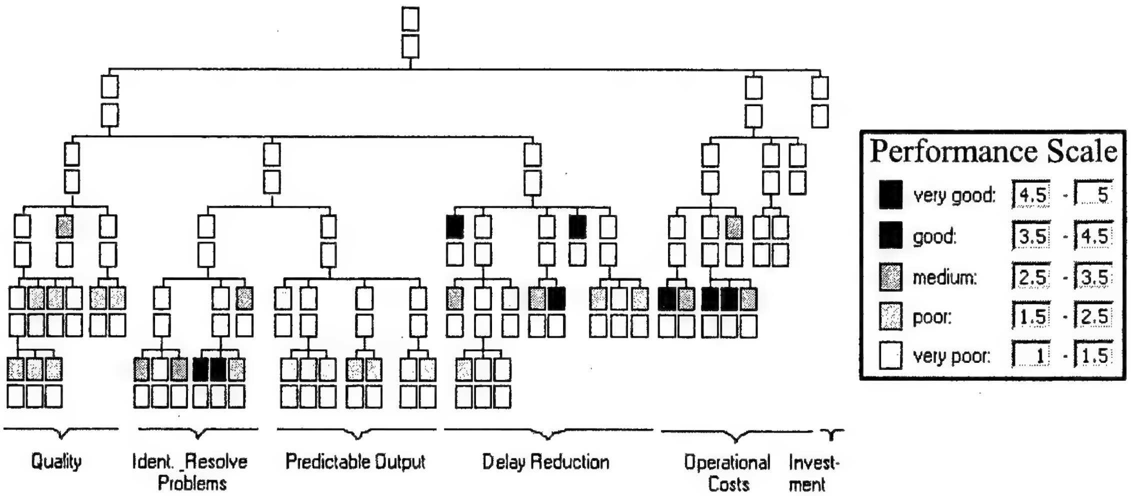


Figure 5-8 Performance Scale

The entire PDS map is then pictured graphically to display the overall "health" of the manufacturing system in question (see

"Before State"	Very Poor	Poor	Medium	Good	Very Good	N/A
Quality	1	7	1	0	0	0
ID&RP	1	1	3	2	0	0
Pred. Output	5	3	0	0	0	0
Delay Red.	3	3	2	3	2	0
Oper. Cost	0	0	3	2	1	0
TOTAL	**10**	**14**	**9**	**7**	**3**	**0**

Figure 5-9). The color-coding from the performance scale depicts each leaf-level FR-DP pair's performance.



"Before State"	Very Poor	Poor	Medium	Good	Very Good	N/A
Quality	1	7	1	0	0	0
ID&RP	1	1	3	2	0	0
Pred. Output	5	3	0	0	0	0
Delay Red.	3	3	2	3	2	0
Oper. Cost	0	0	3	2	1	0
TOTAL	**10**	**14**	**9**	**7**	**3**	**0**

Figure 5-9 Graphical Depiction and Summary of PDS Grading

With an evaluation of the entire manufacturing system, a systematic approach can then be taken to identify strengths and weaknesses and their degree of impact on overall system stability based on the system interdependencies (i.e. the FR-DP logical relationships) as defined by the PDS. Instead of blindly implementing the physical tools of lean without first knowing the *why* and what one is attempting to accomplish in context of the entire system, the PDS evaluation provides a standard, scientific methodology to "lean" continuous improvement activities. Such coherent framework for the overall system that serves as an institutional mechanism for continual improvement is required to stay a step ahead of the competition [Hopp, Spearman, 1996].

CHAPTER 6 WIRE HARNESS ASSEMBLY CASE STUDY

6.1 Introduction

The PDS evaluation form was used to perform a case study at an assembly plant, referred hereafter as 'Company X.' The purpose of performing the case study was two fold:

1. Clearly communicate the achievement of the requirements of the system design and the resulting improvement in system performance
2. Provide a consistent basis for system design and improvement

A standard approach was used to evaluate the wire harness assembly system, which had undergone a recent redesign and provided a good situation to compare the "before" and "after" states of the system. The outline below is used in this chapter:

1. Company and System Background
2. Analysis of the "Before" State
    a. Process Description
    b. Physical Layout
    c. Value Stream Analysis
    d. PDS Evaluation
3. Analysis of the "After" State
    a. Process Description
    b. Physical Layout
    c. Value Stream Analysis
    d. PDS Evaluation
4. Comparison and Correlation of Performance Metrics and PDS Requirement Achievement of the "Before State" and "After State" System Designs
5. Application of the Thinking, Structure and Behavior Framework

6.2 Background

Electrical connectivity throughout the product requires a diverse mix of 122 wiring harnesses, each having its own unique design and varying between 2- 32 feet in length. Wire harnesses consist of twisted pair, single strand, coaxial or fiber optic wires with connectors on each end to provide connectivity to various portions of the product. The wire harness layout in the product is shown in Figure 6-1.

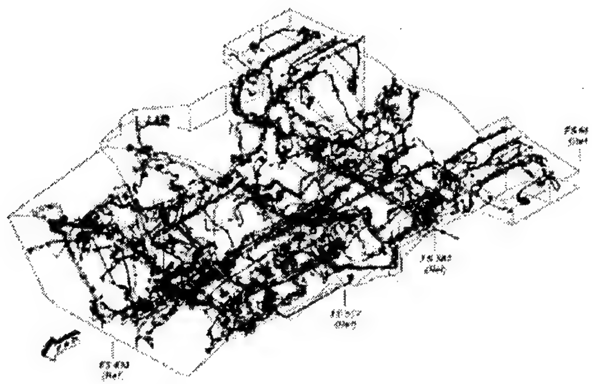


Figure 6-1 Wiring Harness Layout

During the early stages of the assembly program, wire harness assembly was deemed too expensive and the assembly system's delivery to the assembly line was too inconsistent. A company located in Mexico submitted a proposal with a proposed cost being 74% less than Company X's production cost of the wire harness for the last product, #9. If the work was to be retained in-house, the wire harness assembly system had to be redesigned and demonstrate equivalent performance by the completion of the next product's wire harness, #10, 2-3 months away. A cross-functional team of engineering, procurement, industrial engineering, assembly personnel and "lean" department representatives were involved in the redesign effort.

6.3 Analysis of the "Before State"

6.3.1 "Before State" Process Description (in order of sequence)

Each process of the wire harness assembly operations is listed and described. The letter preceding each process depicts its location on Figure 6-3 "Before State" Physical Layout of Wire Harness Assembly.

A. Part Procurement – Required parts and wires were gathered for harness assembly.
B. Cut/Mark – Tubing, tape and wiring were manually measured and cut. Marking the tubing and wiring consisted of applying an identification code in accordance with assembly instructions.
C. Taping – Taping operations were performed on 4'x 8' long plywood boards connected end-to-end on tables dependent on wire harness length (8 ft, 16 ft, 24 ft or 32 ft long). Each of the 122 wiring harnesses required unique assembly boards with the needed configuration of

pegs outlining the harness's assembly pattern. The wires were routed through the pegs and taped or bundled together to secure the configuration (see Figure 6-2).

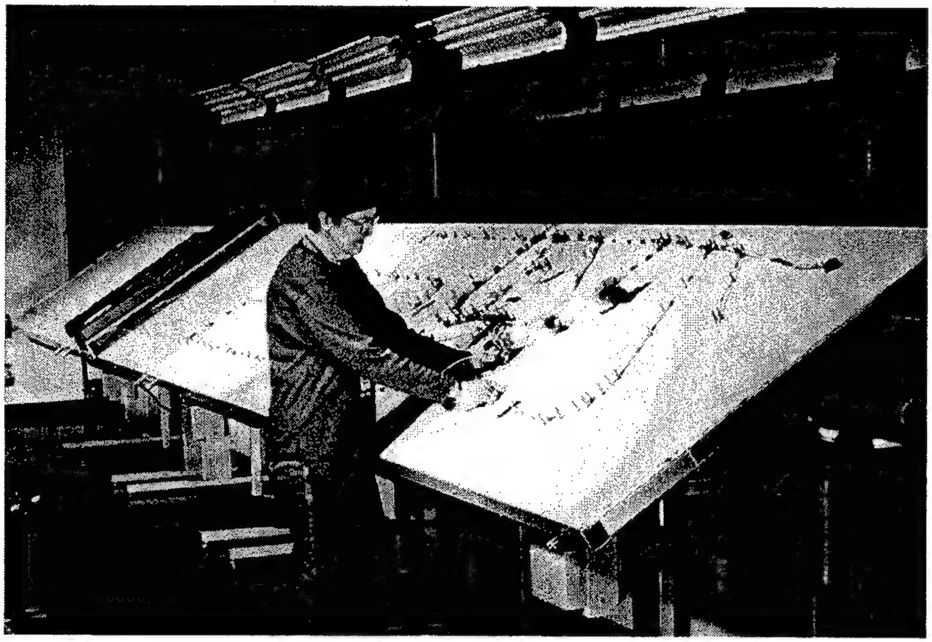


Figure 6-2 Wiring Harness Layout Board

D. Braiding – A machine braided thread into a protective coating around the length of the wires that compressed the harness assembly.
E. End Termination – Terminals were installed on the ends of the wire harness.
F. Testing was performed to ensure connectivity throughout the harness.
G. Dressed Out - The harness was then dressed out, which entailed shrinking of the tubing and placement of the secondary harness identifications.
H. Final Inspection mandated that the harness be laid out on the table for acceptance.

6.2.1 "Before State" Physical Layout

The physical layout, Figure 6-3 below, shows the location of the processes listed in section 6.3.1 and lends to three main observations:

1. The harnesses were placed onto and taken off the table at least three times throughout the assembly process (i.e. for taping, end termination and final inspection).
2. Assembly table areas were split between two separate floors with no standard storage or layout location for a specific board.

3. Transportation distance was approximately 500 ft between consecutive processes. Consequently, each harness traveled nearly one-half mile for all the assembly to occur.

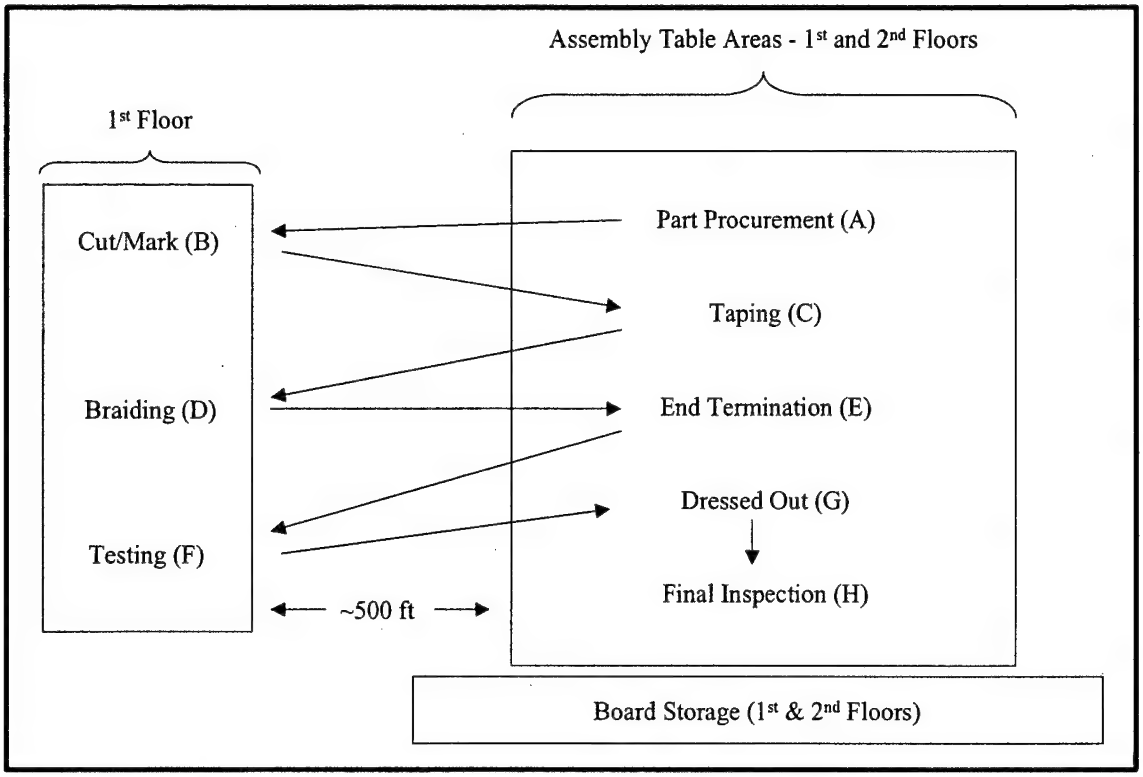


Figure 6-3 "Before State" Physical Layout of Wire Harness Assembly

6.3.3 "Before State" Value Stream Analysis

A value stream of the "before" state was drawn to communicate the material and information flow within the harness assembly cell. Production was controlled by a material requirements planning (MRP) schedule. A production order signaled the release of parts for the cutting and marking of the wiring of a specific harness. Throughout the process, scheduling of work was also initiated and adjusted via MRP. Typically, twenty-five wire harnesses were in production at one time.

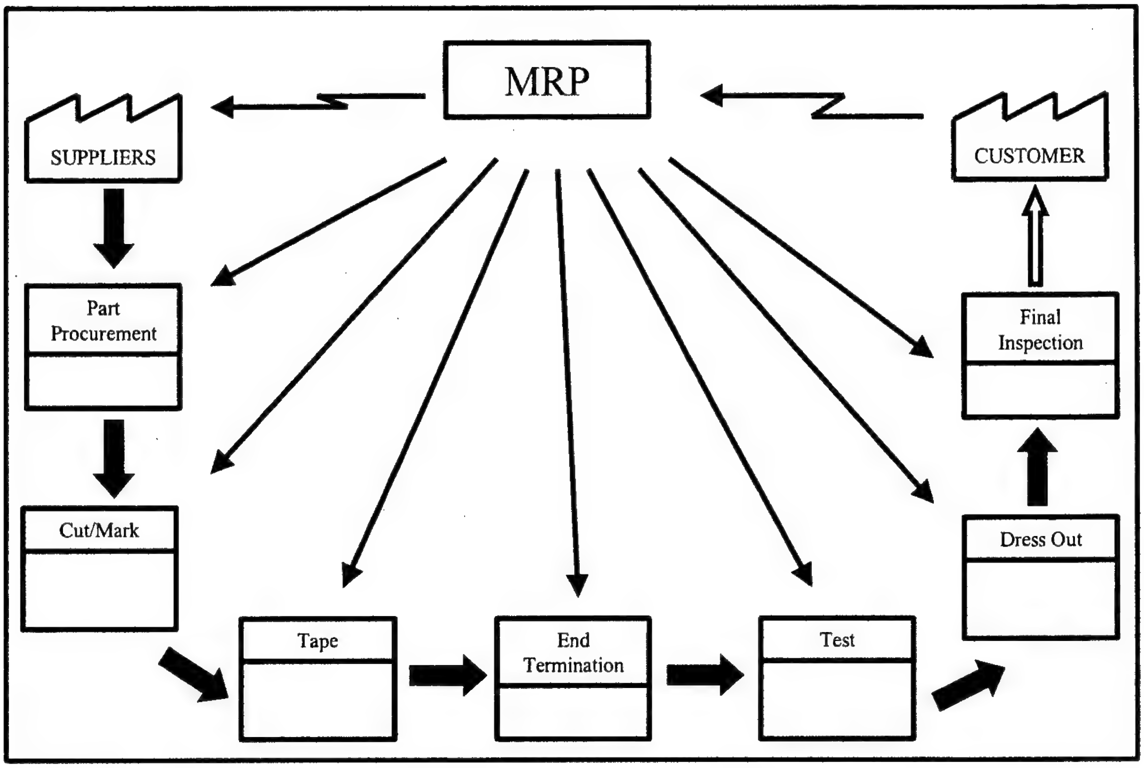
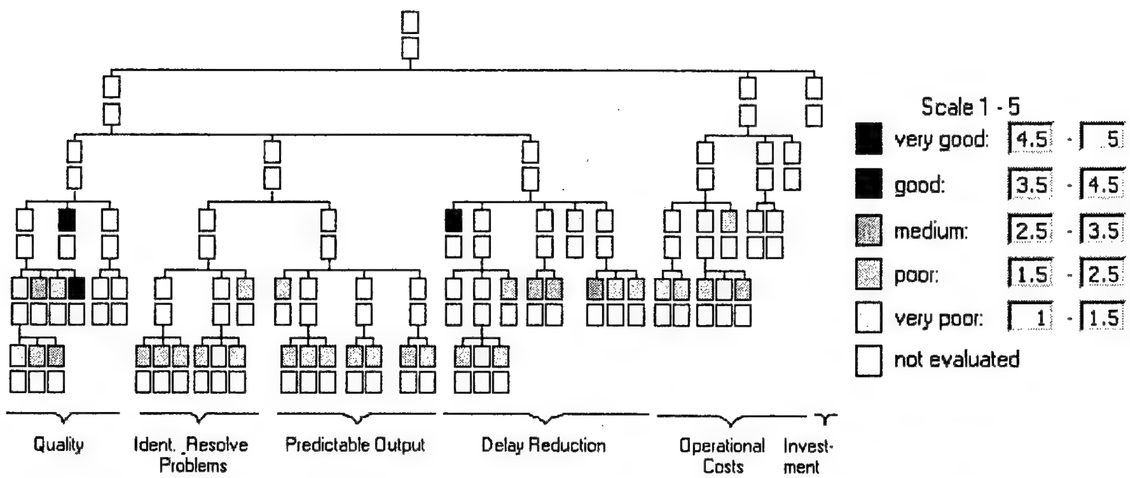


Figure 6-4 Value Stream of "Before" State

6.3.4 "Before State" PDS Evaluation

In addition to a value stream analysis, the "before state" system design was evaluate with the PDS questionnaire with the objective of assessing the degree of requirement achievement. Like a value stream analysis, the PDS evaluation also assesses the material and information flow but also inquires into the variation present in areas of quality, responsiveness of the system to production disruptions, lead-time predictability, length of lead-time and effective use of employees. Operators, a technical specialist, a manager and company lean representatives were involved in the evaluation. The result represents an average of the individual evaluations (see Figure 6-5).



"Before State"	Very Poor	Poor	Medium	Good	Very Good	N/A
Quality	1	2	2	2	0	2
ID&RP	1	6	0	0	0	0
Pred. Output	0	8	0	0	0	0
Delay Red.	3	5	3	0	1	0
Oper. Cost	1	4	1	0	0	0
TOTAL	**6**	**25**	**6**	**2**	**1**	**2**

Figure 6-5 PDS Evaluation of Wiring Harness Assembly – "Before State"

Quality Branch

The "before state" wire harness assembly system graded poorly with respect to quality (see Table 6-1). Training was solely accomplished on the. Standardized work instructions specifying the content, sequence and timing of activities were not clearly defined, accessible or enforced. The workforce, having worked in the plant for years on other programs, was well experienced and knowledgeable of general wire harness assembly tasks. Machinery was quite reliable but no record was kept of manufacturing defects per machine. Also, incoming material was relatively defect free.

"Before State"	Very Poor	Poor	Medium	Good	Very Good	N/A
Quality	1	2	2	2	0	2

Table 6-1 PDS Evaluation of Quality Branch

Identify and Resolve Problems Branch

Identification and resolution of problems scored poorly in relation to the FRs of the PDS (see Table 6-2). Non-standardized material flow paths and physically separated processes

delayed identification of problems and also contributed to slow communication of production disruptions. Resolution of disruptions and their root cause did not occur which led to reoccurrence of the same disruptions, slowing delivery times. Firefighting of problems in attempt to meet schedule consumed resources needed for resolution of the disruptions' root causes.

"Before State"	Very Poor	Poor	Medium	Good	Very Good	N/A
ID&RP	1	6	0	0	0	0

Table 6-2 PDS Evaluation of Identify & Resolve Problems Branch

Predictable Output Branch

Predictable output requirements received poor marks since workers were unable to begin and complete assembly operations per the schedule due to the lack of standardized locations for production resources (i.e. tables, parts, tools) (see Table 6-3). Part presentation to the operator was poor as each harness's parts and wiring were randomly piled on top of one another in plastic tubs and bags. On average, each wiring harness required three boards each, requiring management of nearly 366 individual boards (4'x 8'). More than half of the 122 layout tables were set up at all times on the first and second floors of the building. An assembler had to search for the required boards, which could be in storage or already set up on a table in an unspecified location on either floor. If in storage and once found, a vacant table, on either floor, was then located. Once a vacant table was secured and the layout boards were transported and set up, the operator then sifted through the harness's unorganized supply tub for each specified part. This procedure was repeated until all the harness's wires were in place. Unplanned worker absences also disrupted production. Consequently, predictable output from such a poorly designed system could not occur.

"Before State"	Very Poor	Poor	Medium	Good	Very Good	N/A
Pred. Output	0	8	0	0	0	0

Table 6-3 PDS Evaluation of Predictable Output Branch

Delay Reduction Branch

As with the other areas of the decomposition, the delay reduction branch graded poorly (see Table 6-4). The lone "very good" mark was received due to the fact that the harnesses were not built in batches. Transportation distance (approximately one-half mile per harness) contributed to long assembly times and the process layout was not properly designed to facilitate

one-directional flow of the product. Instead, equipment and process locations were configured with no regard of the material flow of the product or operating pattern of the workers. The multiple lay outs of wire harnesses on the boards that were hard to locate also inflated lead-times. Bottlenecking was also a problem with such operations as the braiding station.

"Before State"	Very Poor	Poor	Medium	Good	Very Good	N/A
Delay Red.	3	5	3	0	1	0

Table 6-4 PDS Evaluation of Delay Reduction Branch

Operational Cost Branch

Personnel were not cross-trained and spent a great deal of time waiting on other operators to finish with an upstream operation. Non-standardized locations for parts, tools, layout boards and production information led to an atmosphere of chaos resulting in unpredictability of system output and thus, high operational cost.

"Before State"	Very Poor	Poor	Medium	Good	Very Good	N/A
Oper. Cost	1	4	1	0	0	0

Table 6-5 PDS Evaluation of Operational Cost Branch

6.4 Analysis of the "After State"

6.2.1 "After State" Process Description (in order of sequence)

Each process of the "after state" wire harness assembly is listed and described with the relevant changes improvements made. Figure 6-9 "After State" Physical Layout of Wire Harness Assembly identifies the location of each process by its name.

A. Kitting - (formally called "Part Procurement") - Instead of delivering a harness' bin to the operator with parts stacked on top of one another, harness parts and wires were kitted using shadow boxes that consisted of foam cutouts for each of a harness's parts. To perform the kitting function, one full time material handler position was added adjacent to the wire cut and marking center. The shadow boxes, varying 2-5 per harness, were placed on moveable racks that could be positioned by the assembler (see Figure 6-6).

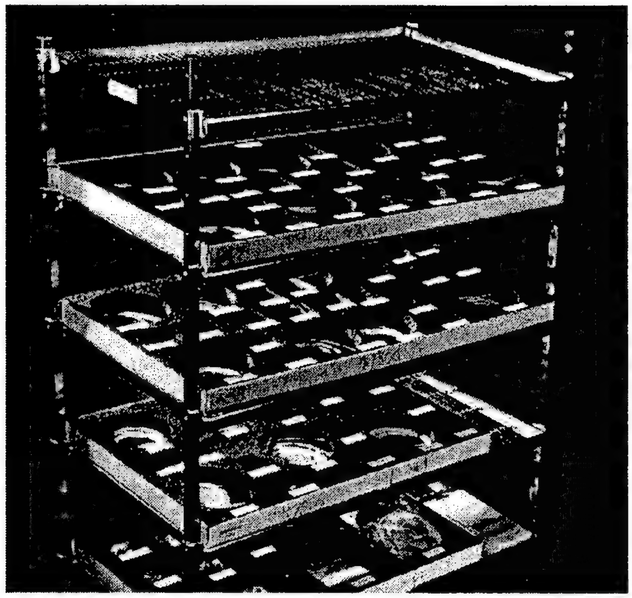


Figure 6-6 Wiring Harness Shadow Box Cart

B. Cut/Mark - In the wire and cut center underwent three significant improvements.

    1. Specialized racks for spools stored over 75 types of wire in a relatively small room and an overhead handling system was setup to assist in loading new racks and reduce the risk of injury to the assemblers.
    2. A wire cutting and laser-marking machine was purchased and connected electronically to the planning database. This allowed automatic and precise cutting and numbering of wires, which identified assembly locations.
    3. A tape-printing machine was modified to electronically access the planning database to eliminate manual input of information and possibility of human error.

C. Sub-Assembly - The current system added a sub-assembly station between the wire cut and marking processes and the layout process. In the "before state" this process was performed in the beginning of the "taping" operation. This L-shaped station installed the connectors on one end of the harness. Work at this station proceeded from left to right with needed parts and tools placed at the point of use of the operator (see Figure 6-7).

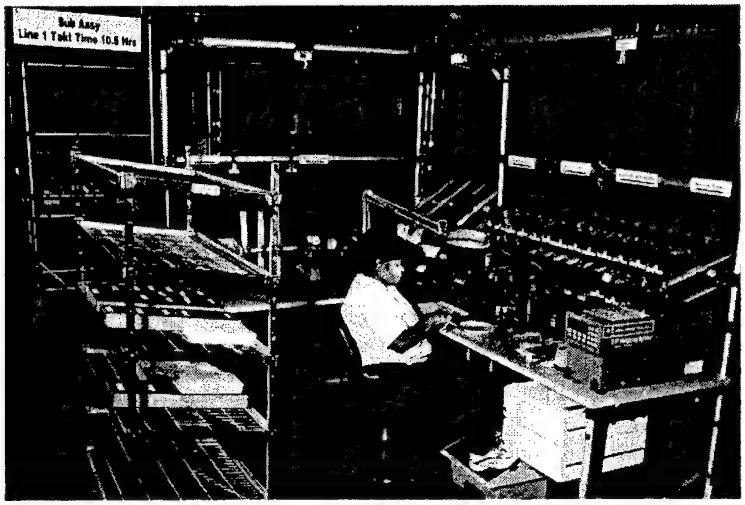


Figure 6-7 Sub-Assembly Station

D. <u>Layout</u> – formally known as "Taping" – The layout process was similar to the "before state" except that the act of laying out the harness on the table is only performed once. To enable this, process standards were modified (i.e. end termination is performed during the "layout" process and final inspection is no longer required to be performed on the layout tables).

E. <u>Braiding</u> – No change in the braiding process occurred except its location - adjacent to the layout area.

F. <u>Harness Transportation</u>, while not a "process" was nonetheless significantly improved. Moveable carts with pegged boards were used to transport the harness from layout to braid and for storage of the test adapters. Instead of rolling up the harness as done in the previous system, the harness is now neatly hung on a pegged board and transported to the braiding operation. Test adapters for each harness were likewise hung on the carts and stored alphabetically adjacent to the test station (see Figure 6-8).

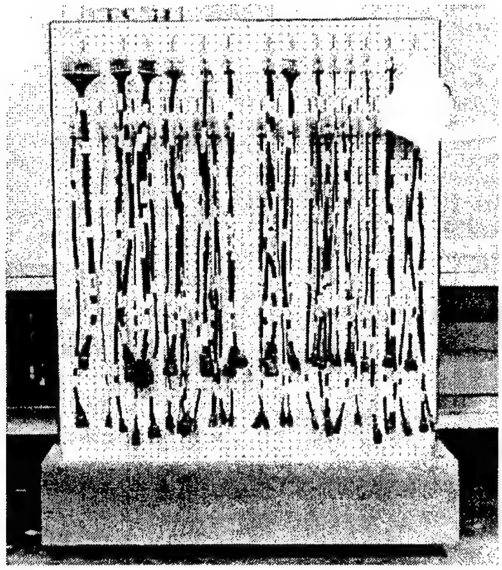


Figure 6-8 Test Adapter Storage & Harness Transfer Cart

G. Testing - In the testing process of the "before" state, testing of individual wires required connection of individual alligator clips. The process was changed to allow bundling of the wire ends to be wrapped with metallic tape; the tape is then hooked to the tester with an alligator clip. As a result, setup time for test was reduced from nearly an hour to minutes per harness.

H. Dress Out & Final Inspection - Previously, dress out and final inspection were performed only while the harness was on the layout table, but now both occur adjacent to the testing location, freeing up the layout boards for assembly of other harnesses in parallel.

6.4.2 "After State" Physical Layout

The physical layout of "after state" demonstrates a significant change from the "before state." All processes have been located adjacent to one another on the same floor of the building (see Figure 6-9).

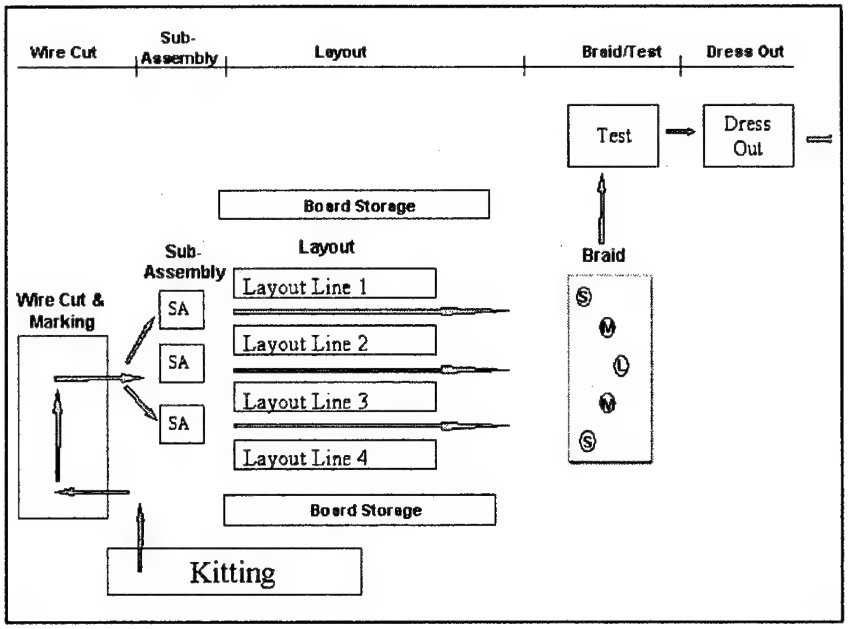


Figure 6-9 "After State" Physical Layout of Wire Harness Assembly

The kits were completed and delivered to one of three sub-assembly stations outside the wire cut and marking room corresponding to its assigned layout line. The arrangement of the layout tables, now called "layout lines," changed significantly. Four 32' tables now replaced the 60+ tables. The harnesses were divided up by layout line depending on the cycle time of each harness. Layout Line #1 assembled harnesses with an average cycle time of 21.5 hours, Line #2 – 13 hours, Line #3 – 9.5 hours and Line #4 – 5.5 hours. To make the work more ergonomic and to eliminate walking distance to work on the other side, layout tables were modified to enable the operator to work from one side (see Figure 6-2 in section 6.3.1).

To enable four such layout lines to handle the workload, the changeover time of the wire harness boards was shortened. The average harness required three 4'x8' boards. Thus, the 122 harnesses equated to approximately 360 layout boards. Two storage areas were created on opposite sides of the layout area. The storage racks were coated with Teflon to allow ease of movement of the boards (see Figure 6-10). Each board was identified by color and alphanumeric designation corresponding to the specific layout line.

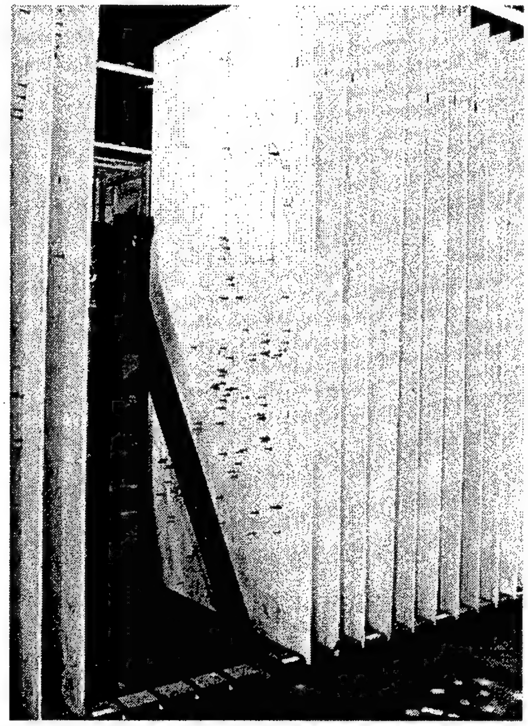


Figure 6-10 Board Storage Area

Portable carts holding all needed tools, operating supplies, and hardware moved to the desired location by the assembler. To re-supply the work carts, a centralized supply location was created.

6.4.3 "After State" Value Stream Analysis

Figure 6-11 below depicts the value stream of the "after" state harness assembly, showing the material and information flow of harness production. MRP is still used only to plan the scheduled delivery of the wire harnesses to the assembly line, but not control the scheduling of internal operations as it did in the "before state." Consequently, upstream processes do not begin until triggered by downstream operations. Movement of harnesses between processes was on a "first-in-first-out" (FIFO) basis.

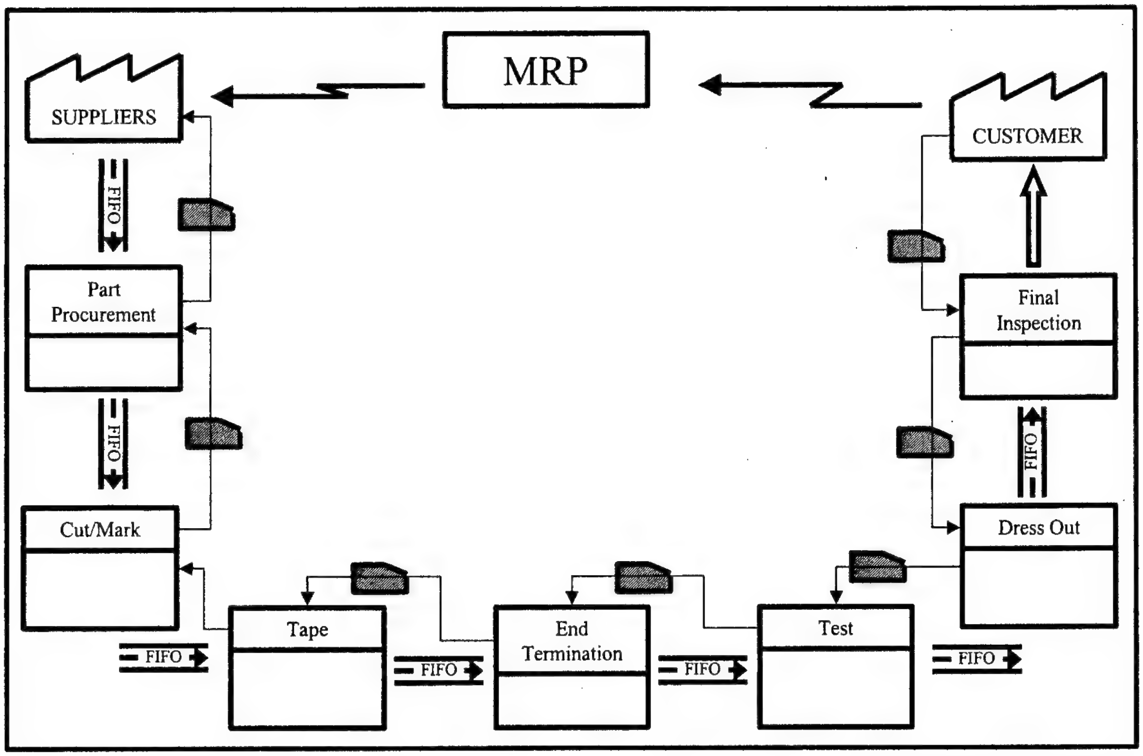
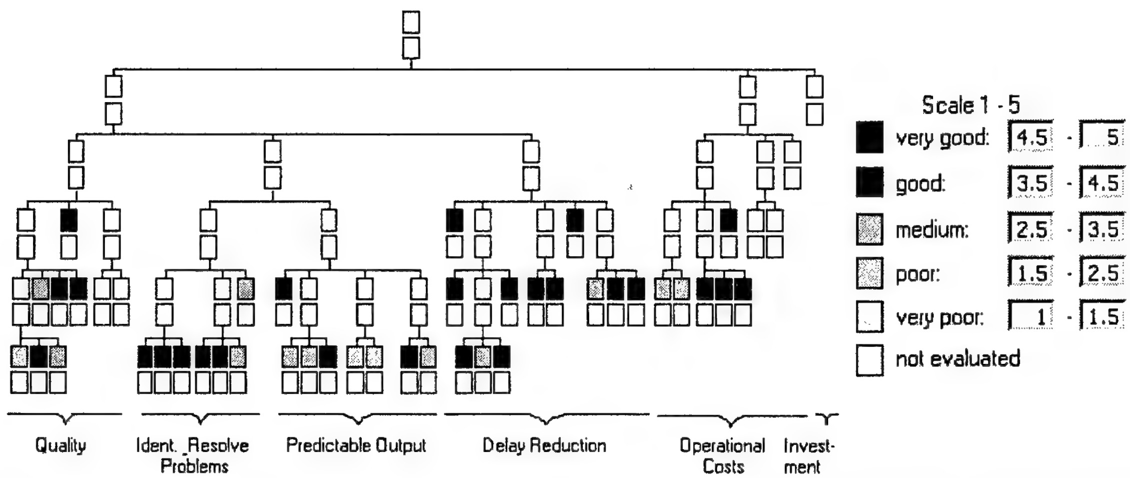


Figure 6-11 Value Stream of "After" State

6.4.4 "After State" PDS Evaluation

The "after" state system design was evaluated with the PDS questionnaire with the objective of assessing the degree of requirement achievement following the redesign (see Figure 6-12). As in the assessment of the "before" state, operators, a technical specialist, a manager and company "lean" representatives were involved in the evaluation. The result represents an average of their individual evaluations.



"After State"	Very Poor	Poor	Medium	Good	Very Good	N/A
Quality	0	0	3	4	0	2
ID&RP	0	0	2	2	3	0
Pred. Output	0	2	3	3	0	0
Delay Red.	0	0	2	7	3	0
Oper. Cost	0	0	2	4	0	0
TOTAL	**0**	**2**	**12**	**20**	**6**	**2**

Figure 6-12 PDS Evaluation of Wiring Harness Assembly – "After" State

Quality Branch

Quality improved moderately from the previous system. Better standardization of work methods now exists, but significant improvement can still be achieved through having usable work instructions at the workstations. Training mainly occurred on-the-job with formalized operator training still non-existent.

"After State"	Very Poor	Poor	Medium	Good	Very Good	N/A
Quality	0	0	3	4	0	2

Table 6-6 PDS Evaluation of Quality Branch

Identify and Resolve Problems Branch

A much more simplified and organized process layout greatly facilitated the immediate detection and communication of disruptions. Shadow boxes enabled the assembler to quickly identify part shortages. A visual work control board was instituted serving multiple functions (see Figure 6-13).

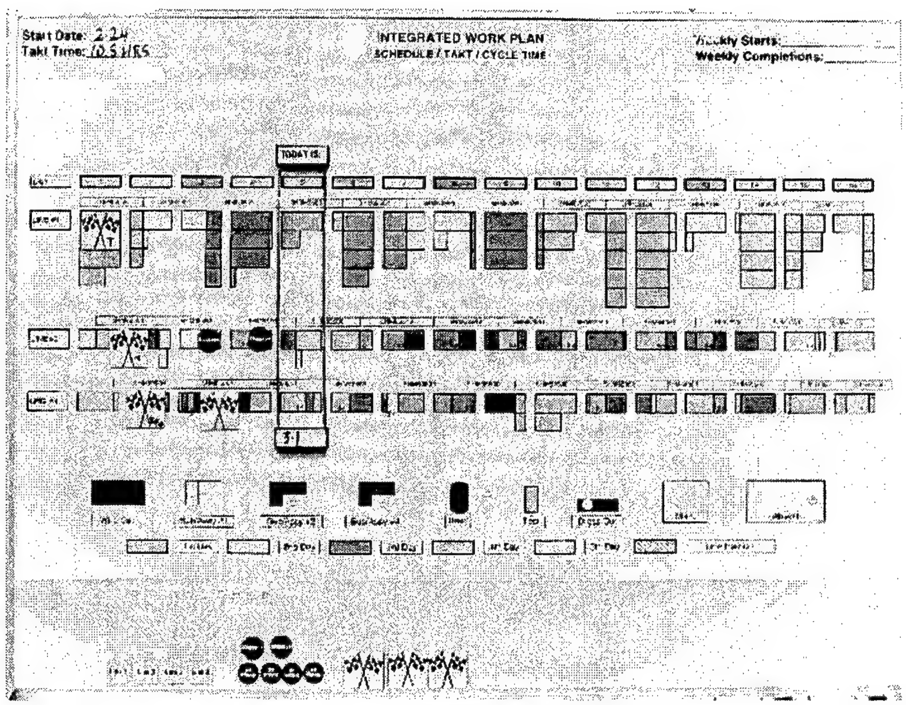


Figure 6-13 Work Control Board

The work control board specified when each harness assembly was to start, how many operators (full and part-time) were required, and on which layout table the harness was to be built. As a management tool, personnel could see whether they were ahead or behind schedule and manpower loading issues could be easily identified.

"After State"	Very Poor	Poor	Medium	Good	Very Good	N/A
ID&RP	0	0	2	2	3	0

Table 6-7 PDS Evaluation of Identify & Resolve Problems Branch

Predictable Output Branch

Predictable output improved but still graded moderately in relation to the PDS. Work completion still varied as almost an entirely new workforce is in operation and training methods remain unimproved. Standardized tool, part locations and resupply area greatly facilitated predictable output. Shadow boxing the parts and wiring also reduced the sorting time of the assembler in the first system, making part shortages immediately apparent. Worker unavailability still was an issue and further cross training of workers was needed on the braiding machine.

"After State"	Very Poor	Poor	Medium	Good	Very Good	N/A
Pred. Output	0	2	3	3	0	0

Table 6-8 PDS Evaluation of Predictable Output Branch

Delay Reduction Branch

The delay reduction branch showed much improvement. To reduce transportation time and distance, all processes were located adjacent to one another on the second floor to ensure a one-way flow of the product. Bottlenecking was greatly minimized with the division of layout lines in accordance with cycle time.

"After State"	Very Poor	Poor	Medium	Good	Very Good	N/A
Delay Red.	0	0	2	7	3	0

Table 6-9 PDS Evaluation of Delay Reduction Branch

Operational Cost Branch

A much greater amount of operator time was dedicated to assembly activities. Preparation time for assembly operations was significantly reduced with the increased level of standardization in board, parts, tools and table locations. Also, less operator time was spent waiting for the resolution of production disruptions.

"After State"	Very Poor	Poor	Medium	Good	Very Good	N/A
Oper. Cost	0	0	2	4	0	0

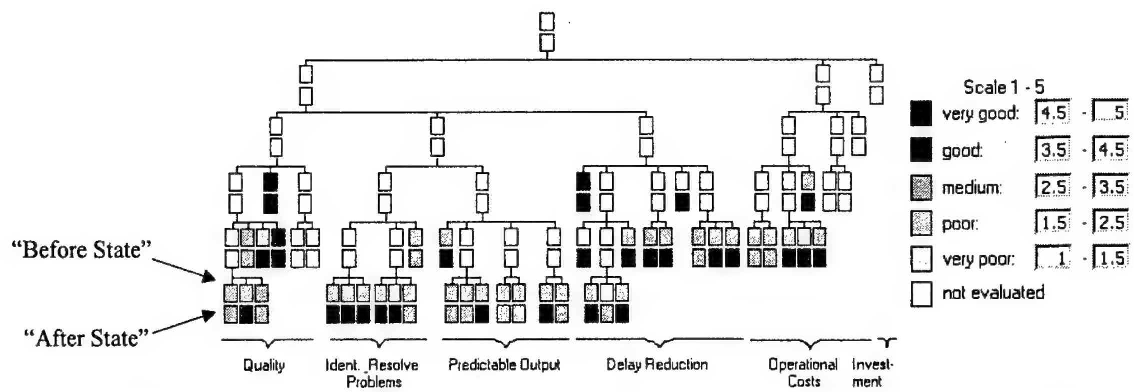
Table 6-10 PDS Evaluation of Operational Cost Branch

6.5 System Comparison

The objective in performing PDS evaluations of the "before" and the "after" state was to determine which PDS requirements are now being achieved in the "after" state system design that previously were not. With this information captured, comparison of PDS requirement achievement to the "before" vs. "after" performance metrics can be evaluated to identify the correlation.

6.5.1 PDS Evaluation Comparison

In Figure 6-14, the PDS evaluations show a significant improvement in the level of requirement achievement from the "before" state to the "after" state of the two harness assembly systems.



TOTAL	Very Poor	Poor	Medium	Good	Very Good	N/A
"Before State"	5	26	6	2	1	2
"After State"	0	2	12	20	6	2

Figure 6-14 PDS Evaluation Comparing of "Before" and "After" States

After the redesign, a significant number of requirements have been achieved more effectively. The value of the logical system design map as defined by the PDS is that it provides a clear picture of the requirements that must be achieved more effectively. The PDS map provides a baseline to communicate a design and to see progress relative to the design.

In the "after state," some PDS requirements are still not being achieved. For example, one of the FR-DP pairs that is not being addressed or even addressed is FR-Q111 "Ensure operator has a knowledge of required tasks" and DP-Q111 "Training Program." The following reasons are offered as to why some FRs were still not being achieved:

1. A systematic system design framework (such as the PDS) was not used to guide the redesign effort, and therefore, the existence of some FRs and significance to the system design may not have been known.
2. The requirement may have been recognized but the requirement but deliberately decided to not address it. The requirement may have been thought to be of minor importance and/or taking the needed actions to meet the requirement was cost prohibitive and would not result in a positive return on investment.
3. The redesign group may have known about the requirement, took what were believed to be proper actions (i.e. implementing the DP), but failed to achieve the requirement.

6.5.2 Performance Metrics and FR Comparison

Table 6-11 depicts the performance of the "before" and "after" system designs.

	Before	After
Production Volume	122 harnesses per 120 days	122 harnesses per 35 days
# Days per Week	5	5
# Shifts per Day	1	1
# Customers	1	1
Distance to Customer	In-house	In-house
In-cell Inventory (# harnesses)	25	11
# Machines	16	17
Cycle Time (days)	120	35
Defects per set of harnesses	4.4	5.0
Rework ($ per product)	567	620
Change over times (min/board)	15 - 20	5
Batch Size (# harnesses)	1	1
# Wiring Harness Styles	122	122

Table 6-11 System Performance Comparison

In order to use the PDS to compare different quantifiable performance of manufacturing systems, the FRs that most directly impact[1] a given set of measurables have been identified [Linck, 2001]. Table 6-12 lists seven major general manufacturing measurables and their corresponding FRs. As indicated by boldface, a number of FRs have been rolled-up to an appropriate parent-level FR. Moreover, an asterix indicates FRs not evaluated in the PDS Evaluation Tool v5.3.

General Mfg. Measurable	*FRs*	*Number of leaf-level FRs*
Floor Area	T4, D21, 123*	2
In-cell Inventory	**P13**, T1, **T3**, **T5**	8
Throughput time	113	12
Direct Labor	**121**	6
Indirect Labor	**R1**, P11, P123, **P13**, **P14**, T51, T53, **122***	15
Labor Hour/Good Parts	**111**, **112**, **113**	36
Rework Cost	**111**, **112**, **113**	36
Bold indicates a PDS branch containing leaf level FRs evaluated herein * indicates FRs not used in the PDS Evaluation Tool		

Table 6-12 Performance Metrics and FRs for Design Comparison

Note - The selection criteria for each FR-measurable relationship asks the question: "does the achievement of the specific FR directly affect the performance of the given measurable?"

Table 6-13 below normalizes the system performance measurables from Table 6-11 above with the "before" state serving as the reference or baseline system. The PDS evaluations were then used to determine the number of FRs achieved with respect to each measurable. An FR is "achieved" if a score of "good" or "very good" on the PDS evaluation is received (i.e. a score of 3.5 or higher).

	Normalized Peformance		**Achievement of FRs**	
Measurable	**Before**	**After**	**Before**	**After**
Floor Area	1	0.59	0 of 2	2 of 2
In-cell Inventory	1	0.43	1 of 8	5 of 8
Throughput time	1	0.29	1 of 12	10 of 12
Direct Labor	1	0.43	0 of 6	4 of 6
Indirect Labor	1	0.5	0 of 15	9 of 15
Labor Hour/Good Harness	1	0.23	3 of 34*	22 of 34*
Rework Cost	1	1.1	3 of 34*	22 of 34*

Table 6-13 Normalized Performance Metrics and FR Achievement Comparison

* Note - Two of the FRs within the quality branch of the PDS did not apply to wire harness assembly and therefore only 34 FRs are considered for "Labor Hour/Good Harness" and "Rework Cost."

All of the measurables show significant improvement and correlate directly to the achievement of PDS requirements except for that of rework cost per set of harnesses, which increased 10% from the "before" state. The following factors contributed to this outcome:

- After the redesign was implemented, the wire harness assembly cell experienced nearly an entire turnover in direct labor (assembly) employees. With no formal training procedures or classes (i.e. entirely on-the-job training), rework cost increased. Had the employee turnover occurred without a redesign effort (during the "before" state), it is proposed that a higher variance in quality would have resulted.
- With new system design, more quality defects are identified and corrected inside the cell before proceeding downstream.

6.6 Application of the Thinking, Structure and Behavior Framework

Performing this case study of the "before" and "after" states of a single system design provides insight into an organization with respect to Figure 6-15 The Thinking, Structure and Behavior Framework below. The difference between the "before" and "after" system states represents a significant change in the thinking of the organization to more of a systems outlook and viewpoint. The company seemed to understand the existence and importance of the interrelationships within a manufacturing system design.

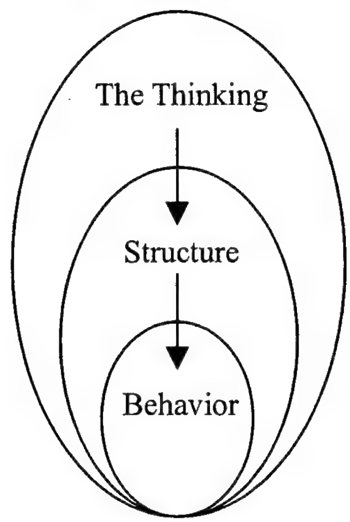


Figure 6-15 The Thinking, Structure and Behavior Framework

At the "Structure" level of the framework, the "before" structure was evidence of the typical American reductionist structure – "divide and optimize the parts with the belief in the optimization of the whole." The organization was forced to abandon this thinking and resultant structure simply because of the crisis imposed by upper management's threat of outsourcing the wire harness assembly. The "after" state structure although aided by recognition of systems thinking, although no framework was used to guide the organization's thinking.

Changes in structure were evidenced by various changes in the wire harness assembly system. Material supply policy was changed with the implementation of a pull system (part replenishment driven by downstream consumption). Additional funding was allocated to the system to allow the purchase of the wire cutting and laser identification machines. Resources in the form of personnel were added to "work on the work" (i.e. improve the way in which the work is performed and organized). Tools were organized in a much different manner. All such

changes represent a change in the thinking of the organization that implies that financial and performance improvement stems from the way in which a manufacturing system is designed.

At the time of the system redesign, the company was implementing "lean" tools or principles. In actuality, the resulting performance improvement came from achievement of the requirements of a system design as defined by the PDS. As is seen in the case study, the PDS evaluations of the "after" state show significant areas of improvement were yet needed. So, the question is asked, "Is the wire harness assembly cell, lean?" With many areas of improvement yet to be addressed, this redesign effort represents the first of many such efforts that should be undertaken. The system design is not complete until all the requirements as defined by the PDS are fully achieved. Until all PDS requirements are achieved, cost will not fully be eliminated and system instability will yet remain. The achievement of the FRs of a system design directly results in measurable performance improvements and thus, better business results. This case study further validates the PDS as a reliable indicator and predictor of bottom line system performance and further communicates the cost and system instability associated from not meeting the requirements of a system design.

CHAPTER 7 A METHODOLOGY TO SUPPORT MANUFACTURING SYSTEM DESIGN IMPLEMENTATION

7.1 Introduction

The objective of this paper is to present the development and application of a methodology that applies axiomatic design in the allocation of constrained resources to achieve system design requirements (Cochran et. al, 2002). The method presented is a new approach that leads to the prioritization and selection of improvement projects that have the greatest potential to achieve system design requirements when a company has limited resources.

7.2 The Industry Problem

Industry struggles to achieve the six requirements of system stability, leading to higher manufacturing costs [Johnson, Broms, 2000] [Cochran, 1999]. Consequently, continuous improvement projects are undertaken. Industry lacks a scientific approach to identify and select improvement projects [Cochran et. al, 2000]. The PDS provides a scientific basis for the development of such an approach.

The 'health' of an existing manufacturing system design can be evaluated with a questionnaire based on the PDS [Cochran et. al, 2000]. When an FR as defined by the PDS is not fully achieved, unnecessary system instability and cost are incurred. Cost is the direct result of the system design [Cochran, 1994]. Only when the manufacturing system is stable can waste be permanently reduced. When true waste is reduced, true cost is reduced [Cochran et. al, 2000] [Johnson, Broms, 2000] [Cochran, 1999]. DP implementation to fully achieve the FR often requires additional investment and/or resources. Industry commonly assumes the cost/investment of fully implementing a DP to be prohibitive. Thus, companies unknowingly and inevitably have much higher costs resulting from system instability (e.g. fighting fires, expediting, holding 'what-can-we-make-today meetings,' making defective products, etc.) [Deming, 2000].

7.3 Investment and Resource Allocation Methodology Derivation

The goal of the enterprise must be to fully achieve the system design requirements as stated in the PDS [Cochran et. al, 2000]. In situations where the enterprise's resources are constrained, knowledge of path dependency in the PDS design matrix can be used to develop an

investment and resource allocation methodology. This methodology enables management to prioritize and select improvement projects based on their sensitivity with respect to FR achievement.

As a foundation for this methodology, the FRs and DPs are related to measurable monetary units. Investment (IV) in a DP results in benefits (BF) from achievement of the FRs (see Figure 7-1).

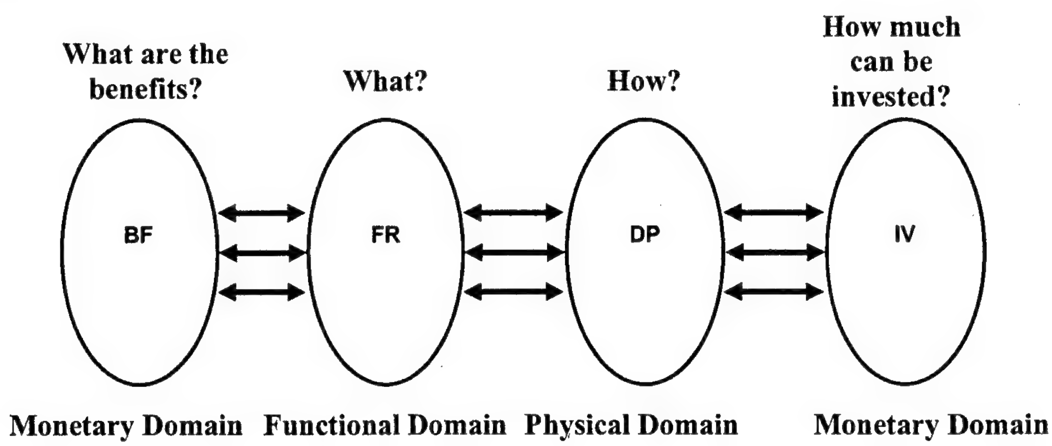


Figure 7-1 Conversion process from monetary investment to monetary benefits

The current state of each FR must be known and full achievement of each FR is the goal [Cochran et. al, 2000]. Higher FR achievement will result in benefits that can be monetarily quantified. Improvement in FR achievement requires investment towards its path dependent DPs. Comparing estimated benefits to the required investment enables effective utilization of limited resources.

In order to quantify the relationships between FRs and DPs, performance measures for both are a preliminary necessity. FR achievement can be quantified by the performance metrics defined in the PDS.

A new cost matrix [R] is derived (see Equation 7-1) to quantify the benefits (BF) resulting from investments (IV). Rij is an expression in monetary units of the sensitivity of benefit resulting from the increase in FRi achievement caused by investment in DPj (i.e. return on investment from investing in DPj).

$$R_{ij} = \frac{\partial BF_i}{\partial FR_i} * \underbrace{\boxed{\frac{\partial FR_i}{\partial DP_j}}}_{A_{ij}} * \frac{\partial DP_j}{\partial IV_j} = \frac{\partial BF_i}{\partial IV_j}$$

Equation 7-1 Differential Form of Cost Matrix Element

7.4 Simplified Model – Single FR-DP Pair

For a linear design, the design matrix elements (Aij) are constants; for a nonlinear design, Aij are functions of the DPs [Suh, 2001]. It is the authors' belief that most Aij are not constant over the range of implementation, but vary in shape. In practice, companies will be able to use any baseline cost curves they have developed, and as they undertake a continuous portfolio of projects, they will be able to establish cost curves for each FR. For simplicity in model development, the Aij functions have been assumed to take the shape of normal cost curves.

The following model is based on two assumptions:

1. In order to simplify the model, one DP only affects one FR (Section 7.4 only).
2. The occurrence of investment and benefit are at the same point in time. In reality the benefits will be realized at a later point in time and discounted.

The formula of the R-element is partitioned (see Equation 7-2).

Benefit received by
achieving FRi caused
by improving one DPj

$$R_{ij} = \boxed{\frac{\partial BF_i}{\partial FR_i} * \frac{\partial FR_i}{\partial DP_j}} * \boxed{\frac{\partial DP_j}{\partial IV_j}}$$

Improvement in one DPj
caused by investment in
DPj

Equation 7-2 Partitioned R element

Figure 7-2 below depicts the sensitivities of the two components in Rij. To express both components with the monetary term in the numerator, the second component ($\partial DPj / \partial IVj$) was inversed. This graph is based on the assertion that investment in a DP can only become prohibitive once the FR has been fully achieved in the eyes of the internal and external customers. Therefore, the point of intersection represents the absolute full FR achievement. In other words, an additional dollar should be invested in DPj as long as the benefits are greater than the investment at any point in time.

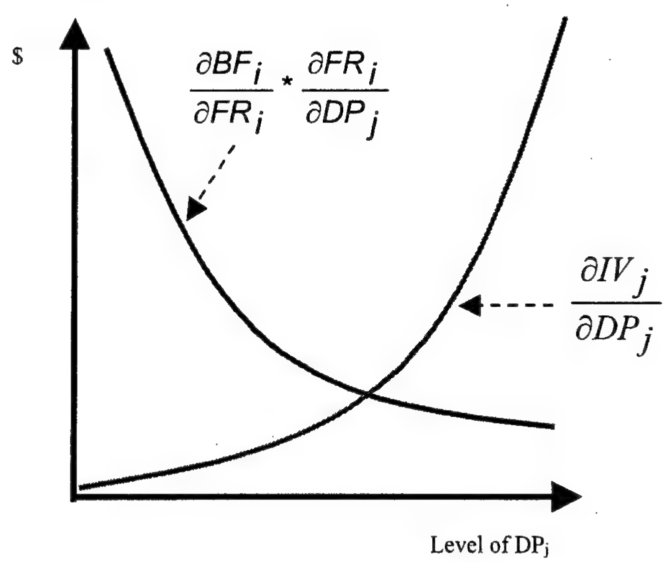


Figure 7-2 Sensitivity of Benefit to Investment

The curves in Figure 7-2 are based on the following assumptions:

1. The degree of benefit to be gained from higher FRi achievement declines with increasing levels of DPj implementation.
2. The amount of investment required to improve DPj increases with higher levels of DPj implementation.

These assumptions are believed to be generally applicable but must be examined in future case studies.

Incremental investment in a DP is profitable in the region to the left of the point of intersection in Figure 7-2. The mathematical expression for this statement is:

$$\frac{\partial IV_j}{\partial DP_j} \le \frac{\partial BF_i}{\partial FR_i} * \frac{\partial FR_i}{\partial DP_j}$$

Equation 7-3 Investment Performance Sensitivity

or restated:

$$R_{ij} = \frac{\partial BF_i}{\partial FR_i} * \frac{\partial FR_i}{\partial DP_j} * \frac{\partial DP_j}{\partial IV_j} \ge 1$$

Equation 7-4 Investment Performance Sensitivity

7.5 Complete Model – Multiple FR-DP Relationships

Assumption #1 in Section 4 is now retracted. Within the PDS, DP-Q121 (Training program) does not only affect FR-Q121 (Ensure that operator has knowledge of required tasks), but also FR-Q122 (Ensure that operator consistently performs tasks correctly) (see Figure 7-3). This is one example of the path dependent nature as defined by the PDS.

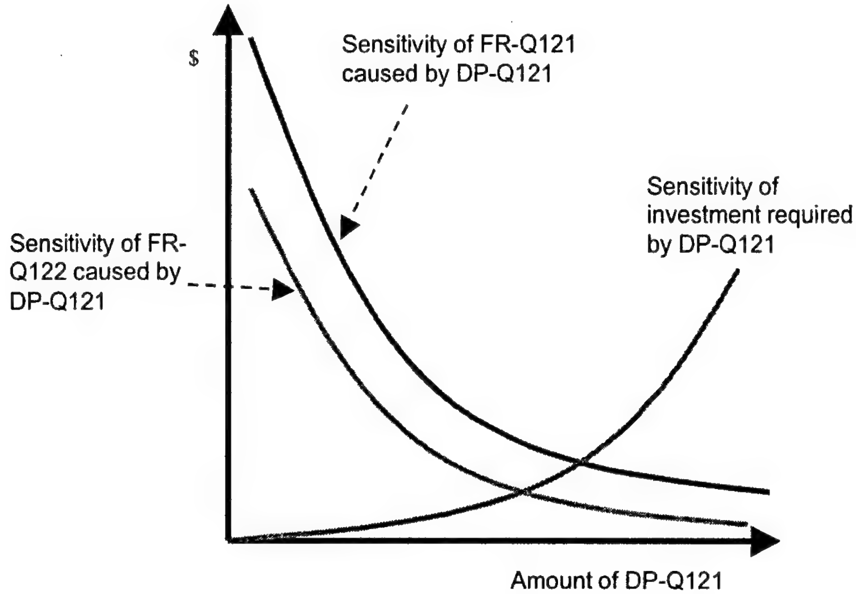


Figure 7-3 Sensitivity of Benefit to Investment – Multiple FR Case

The benefit from FR-Q122 is smaller than the benefit from FR-Q121, because FR-Q122 is mainly influenced by DP-Q122. The total benefit caused by further implementing a single DP is the sum of the individual benefits gained from better achievement of all path dependent FRs (see Figure 7-4).

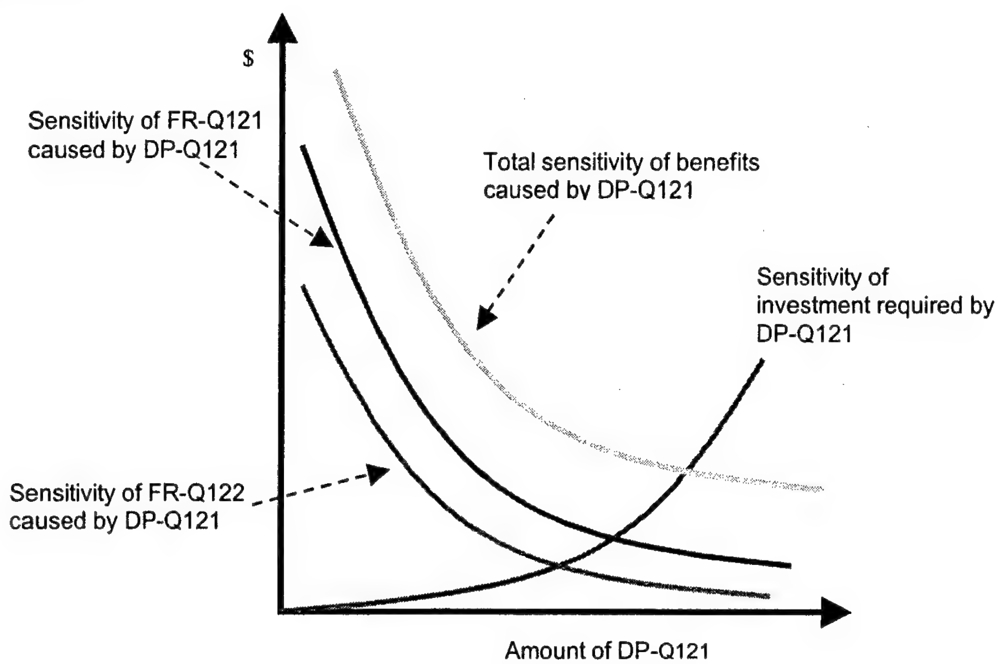


Figure 7-4 Total sensitivity of implementing DP-Q121

Mathematically, the allowable investment in DP-Q121 (from Figure 7-4) can be expressed as follows:

$$\frac{\partial IV(Q121)}{\partial DP(Q121)} \leq \frac{\partial BF(Q121)}{\partial FR(Q121)} * \frac{\partial FR(Q121)}{\partial DP(Q121)} + \frac{\partial BF(Q122)}{\partial FR(Q122)} * \frac{\partial FR(Q122)}{\partial DP(Q121)}$$

Equation 7-5 Investment Performance Sensitivity – Multi FR Case

The amount of resources that can be invested in DP_j must be less than or equal to the cost of not achieving (i.e. the benefits) FR_i and all path dependent FRs (see Equation 7-6).

$$IV(DP_j) \leq \sum_{i=1}^{n} BF(FR_i)$$

Equation 7-6 DP Investment Decision Equation

Equation 7-5 can be restated as:

$$1 \leq \frac{\partial BF(Q121)}{\partial FR(Q121)} * \frac{\partial FR(Q121)}{\partial DP(Q121)} * \frac{\partial DP(Q121)}{\partial IV(Q121)} + \frac{\partial BF(Q122)}{\partial FR(Q122)} * \frac{\partial FR(Q122)}{\partial DP(Q121)} * \frac{\partial DP(Q121)}{\partial IV(Q121)}$$

Equation 7-7 Investment Performance Sensitivity – Multi FR Case

Where:

$$R_{ij} = \frac{\partial BF_i}{\partial FR_i} * \frac{\partial FR_i}{\partial DP_j} * \frac{\partial DP_j}{\partial IV_j}$$

Equation 7-7 can now be expressed as:

$$1 \leq R_{BF(Q121),IV(Q121)} + R_{BF(Q122),IV(Q121)}$$

Equation 7-8 Investment Performance Sensitivity – Multi FR Case

Hence an investment should be considered as long as the sum of the sensitivities from all path dependent FRs is greater than one.

Or as a general expression:

$$1 \leq \sum_{i=1}^{n} R_{BF(FR_i),IV(DP_j)}$$

Equation 7-9 Investment Performance Sensitivity – Multi FR Case

Once the benefit sensitivities are summed for each DPj, improvement projects (DPs) can then be prioritized based on the summed benefit sensitivities [R_j] from the greatest to least with 1.0 serving as the lower limit for improvement projects. This will ensure the most effective allocation of constrained company resources.

7.6 Analysis of Benefits

To implement Equation 7-7 above, a clear understanding is required of calculating and evaluating the costs and the benefits from investing in a DP or a portfolio of DPs. Benefits can be evaluated over the lifecyle of the project. Within different organizations, the determination of the lifecycle will be case specific. However, once a credible lifecycle can be established, a variety of techiques can capture and measure the benefits of a system improvement project. Quantatively, most methods rely on discounted cashflows (DCF), with net present value (NPV) and real options valuation (ROV) being two examples.

7.7 Implementation

In practice, the following steps are recommended:

1. System design evaluation to identify the health of the current system.
2. Valuation of FRs not fully achieved - estimate the potential benefits to be gained from each FR. If the benefit to an FR cannot be quantified, denote with a '+'.
3. DP contribution - understand the path dependency between valued FR to multiple DPs to derive the total contribution of a DP.
4. DP project valuation - calculate the investment required for the project to further implement a DP.
5. Undertake an NPV or ROV analysis of the expected benefits from achieving the FRs resulting from the investment in the DP.

7.8 Case Study

Professor Cochran and his group worked with a manufacturing company facing challenging cost targets and having limited available resources. Management was seeking a scientific methodology to define their production system and guide their decision-making. Data were not readily available on the cost incurred from not fully achieving the PDS requirements. Management estimated this cost to be about one-half of the current assembly (direct labor) time per product. To determine the cost of not achieving the requirements, the three most recent products to complete production were used as a baseline.

Accurately quantifying the impact of each PDS requirement not being met was nearly impossible, but from program metrics and data available, only the following PDS requirements and solutions could be estimated.

FR-111 'Design products that meet program requirements'
DP-111 'Product Design Process'

FR-Q1 'Manufacture products within engineering requirements'
DP-Q1 'Elimination of assignable causes of variation'
(i.e. non-conformance work)

FR-P11 'Ensure availability of relevant production information'
DP-P11 'Capable and reliable information system'
(i.e. unavailable, late, incomplete, inadequate, or unclear work instructions)

FR-P12 'Ensure tools and supplies are available'
DP-P12 'Processes to ensure adequate supplies'

FR-P132 'Ensure availability of workers'
DP-P132 'Attendance policy enforcement'
(i.e. 'labor loss' - excessive, insufficient or untrained workforce compared to requirements)

FR-P15 'Ensure material availability even though fallout exists'

DP-P15 'Standard material replenishment approach'

(i.e. part shortages)

Figure 7-5 below shows the PDS with the quantified FR-DP pairs identified in red.

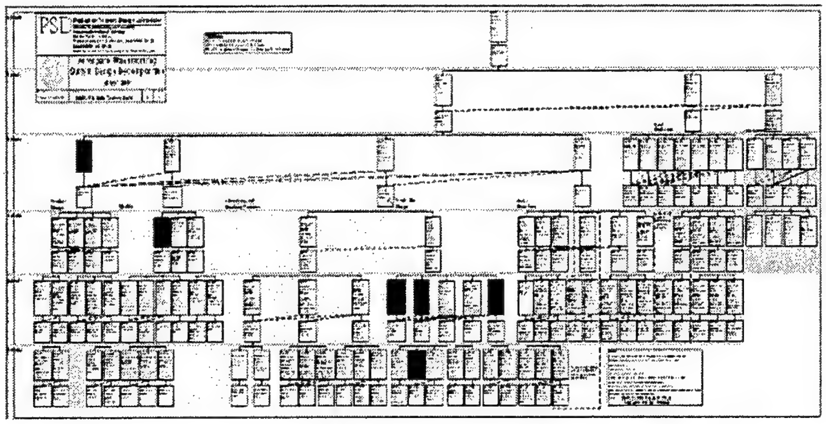


Figure 7-5 PDS Requirements Studied

Direct labor cost per product was estimated for each of the above requirements while indirect (non-assembly) cost per product was only estimated for FR111, FR-Q1, FR-P12 and FR-P15. Total program cost was calculated by summing the direct and indirect costs.

The graph in Figure 7-6 below displays the total labor hours per product incurred from not fully achieving six PDS requirements (not accounting for path dependency).

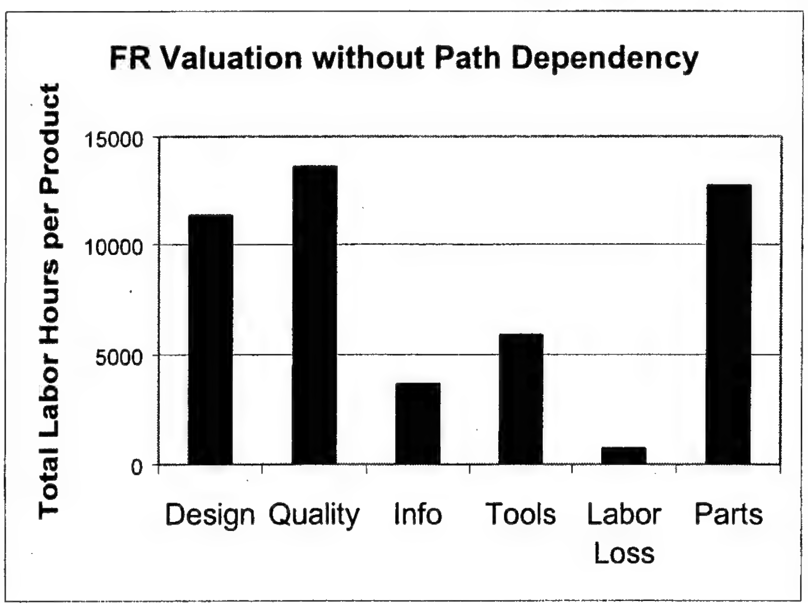


Figure 7-6 FR Valuation without Path Dependency

Because the PDS represents a path dependent design, investment in one DP will have a positive affect on multiple FRs. To more accurately estimate the allowable investment in each of the above DPs, the path dependency must be determined as shown in Equation 7-10 and Equation 7-11.

$$\begin{Bmatrix} FR-111 \\ FR-Q1 \\ FR-P11 \\ FR-P12 \\ FR-P132 \\ FR-P15 \end{Bmatrix} = \begin{bmatrix} X & - & - & - & - & - \\ X & X & - & - & - & - \\ X & X & X & - & - & - \\ X & - & X & X & - & - \\ - & - & - & - & X & - \\ X & X & X & - & - & X \end{bmatrix} * \begin{Bmatrix} DP-111 \\ DP-Q1 \\ DP-P11 \\ DP-P12 \\ DP-P132 \\ DP-P15 \end{Bmatrix}$$

Equation 7-10 Path Dependency of Studied PDS Requirements

Management estimated the magnitude of the design matrix elements (see Equation 7-11). For example, 90% of the cost of not fully achieving FR-Q1 'Manufacture products within engineering requirements' was due to poor implementation of the direct DP, DP-Q1 'Manufacture products within engineering requirements,' and the other 10% of the cost was incurred from not fully implementing DP-111 'Design products that meet program requirements.'

$$\begin{Bmatrix} FR-111 \\ FR-Q1 \\ FR-P11 \\ FR-P12 \\ FR-P132 \\ FR-P15 \end{Bmatrix} = \begin{bmatrix} 1.0 & - & - & - & - & - \\ 0.1 & 0.9 & - & - & - & - \\ .03 & .03 & .94 & - & - & - \\ 0.8 & - & .05 & .15 & - & - \\ - & - & - & - & 1.0 & - \\ .01 & .02 & .01 & - & - & .96 \end{bmatrix} * \begin{Bmatrix} DP-111 \\ DP-Q1 \\ DP-P11 \\ DP-P12 \\ DP-P132 \\ DP-P15 \end{Bmatrix}$$

Equation 7-11 Path Dependency Contribution

The previous bar chart (Figure 7-6) is then modified according to the degree of the path dependency indicated in Equation 7-11 (see Figure 7-7). Consideration of the path dependency in the system design identifies and more accurately estimates the allowable investment in each of the DPs from the costs incurred from not fully achieving specific FRs.

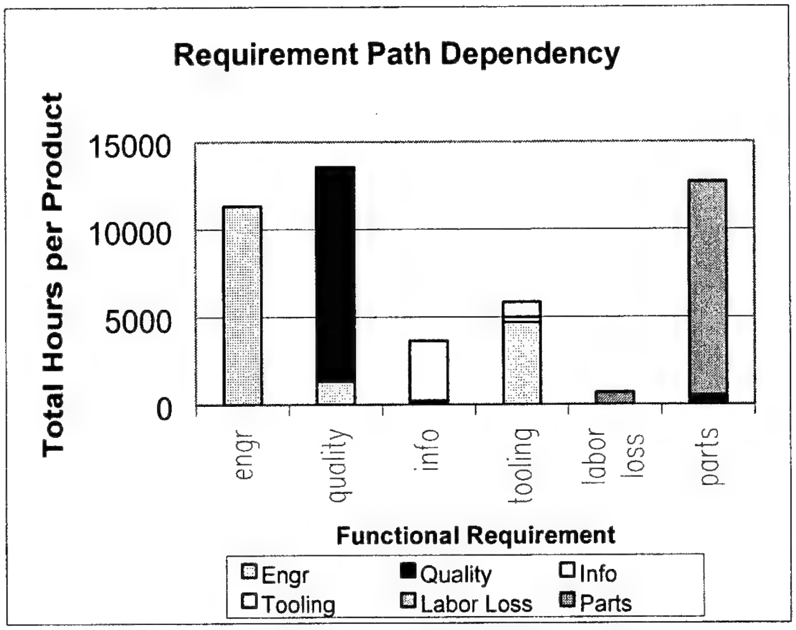


Figure 7-7 FR Valuation Based on Path Dependency

For example, as seen in Figure 7-7, not fully implementing the engineering DP (DP-111) affects not only the achievement of its direct FR (FR-111), but also has significant effects on achievement of quality (FR-Q1) and tooling (FR-P12) requirements. Figure 7-8 shows the summation of each DP's effect on their own direct FR and their path dependent FRs (i.e. depicted by summing the elements of each column in the design matrix [A]).

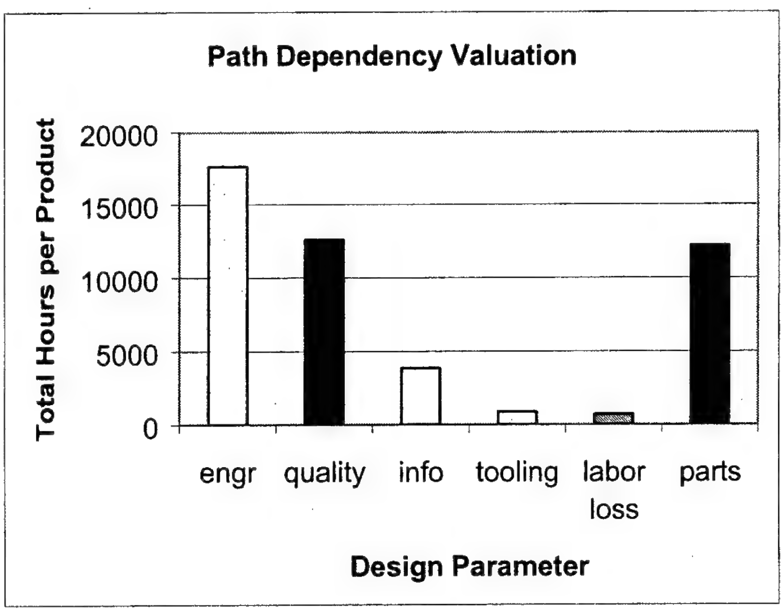


Figure 7-8 Allowable Investment in each DP

Accounting for path dependency yielded a more accurate estimate of the allowable investment in each of the DPs. For example, the allowable investment in engineering DP-111 increased 55% over DP-111's previous value as shown in Figure 9.

The PDS represents a system design in its entirety. Every FR must be achieved for the design to be complete. However, given limited resources, the knowledge of the path dependent relationships provides a scientific basis for the allocation of resources.

7.9 Conclusion

This paper develops a scientific approach based on the Product Delivery System to identify, evaluate and select continuous improvement projects, which have the greatest leverage to achieve system stability. The design matrix [A] defined in axiomatic design was used to derive a cost matrix [R]. The cost matrix enables comparison of potential improvement projects with respect to the path dependency as defined in the Product Delivery System. Hence, in the presence of constrained resources, improvement projects can now be evaluated and selected based on their potential leverage to achieve system stability requirements.

CHAPTER 8 CONCLUSIONS AND RECOMMENDATIONS

8.1 Thesis Conclusions

This thesis documents research providing evidence for the theory that desired business results are the direct result of the system's design. The research primarily addressed manufacturing system design but it is presumed that the system design approach documented herein can be used to design of systems of various types (i.e. organizational, software, integrated, enterprise and hardware).

Chapter two defines the central theme applied throughout the development of this thesis, being the 'thinking' creates the 'structure', which then drives the 'behavior' of a system. It was concluded that behavior, actions, performance, quality, cost and culture cost, culture, physical design, and classifications describing systems as either 'mass' or 'lean' are solely the results of a system design or structure. Achievement of enduring change in the performance of a system must begin with a change in thinking of all people in the enterprise, especially that of leadership. In the absence of such a change in the thinking, structural change within the system will be short-lived and may only result in optimization of localized sub-systems instead of systemic improvement.

Chapter three identifies and analyzes the structure and resulting behavior of 'mass thinking.' This way of thinking represents a belief that if the performance of each sub-system or piece-part of the system is maximized, the overall performance of the system as a whole is maximized. The structure resulting from this way of thinking is the unit cost equation. Such structure results in unstable systems that are not robust to operation variation or economic volatility and consequently are less profitable.

Conversely, chapter four identifies and analyzes a second way of thinking, 'systems thinking,' which states that high-level systemic performance is achieved by not only focusing on the performance of the system's elements, but especially their interdependencies and influences on and between other system elements. Axiomatic design is presented as the structure or design methodology to best reflect, understand and control the complexity inherent in the design of large-scale integrated systems. By successfully focusing on the logical aspect of the design (i.e. the FR-DP mapping) prior to progression into costly physical design, much developmental time and cost can be avoided. The result of such a system design approach is represented by stable

systems, which completely achieve all the requirements of the internal and external customers in spite of variation occurring within the system.

Chapter six presents a case study comparing the 'before' and 'after' states of the redesign of a manufacturing cell. Results of the case study demonstrated a direct correlation between achievement of the PDS requirements and improved system performance. The case study further validated the application of the PDS in the green field design a stable system or in the redesign an existing system.

Chapter seven set forth the development and application of an investment and resource allocation methodology to support manufacturing system design implementation. The methodology is a new approach that can be used by a company with constrained investment resources to target and prioritize potential continuous improvement projects to most effectively apply limited resources to ensure the greatest increase in system stability.

Chapter eight defined and addressed the application of the Logical System Design Model in a major manufacturing company. The application succeeded at a sub-system level within the enterprise but has not yet been able to seed organizational change and expand its acceptance and propagation at the enterprise level.

8.2 Recommendations for Future Research

System Stability

Research is yet needed with respect to the manner in which to best teach and communicate the concept of system stability. The manufacturing industry greatly struggles with the achievement of system stability for two reasons. First, most of academia has yet to understand and sufficiently teach it. Secondly, because academia is not solving the problem, industry is turning to consultants who are promoting the latest buzzwords-of-the-month with minimal, enduring and substantive results.

System stability is succinctly and thoroughly described by the six requirements of system stability as defined by Prof David Cochran. It is believed that more research is needed in the teaching methodologies of system robustness (R5) and standard and immediate problem solving (R6). Without a proper understanding of the importance of achieving these two requirements and creating the environment necessary to seed the organizational changes required to implement

the requirements, industry will not be able to fully appreciate and achieve stable manufacturing systems.

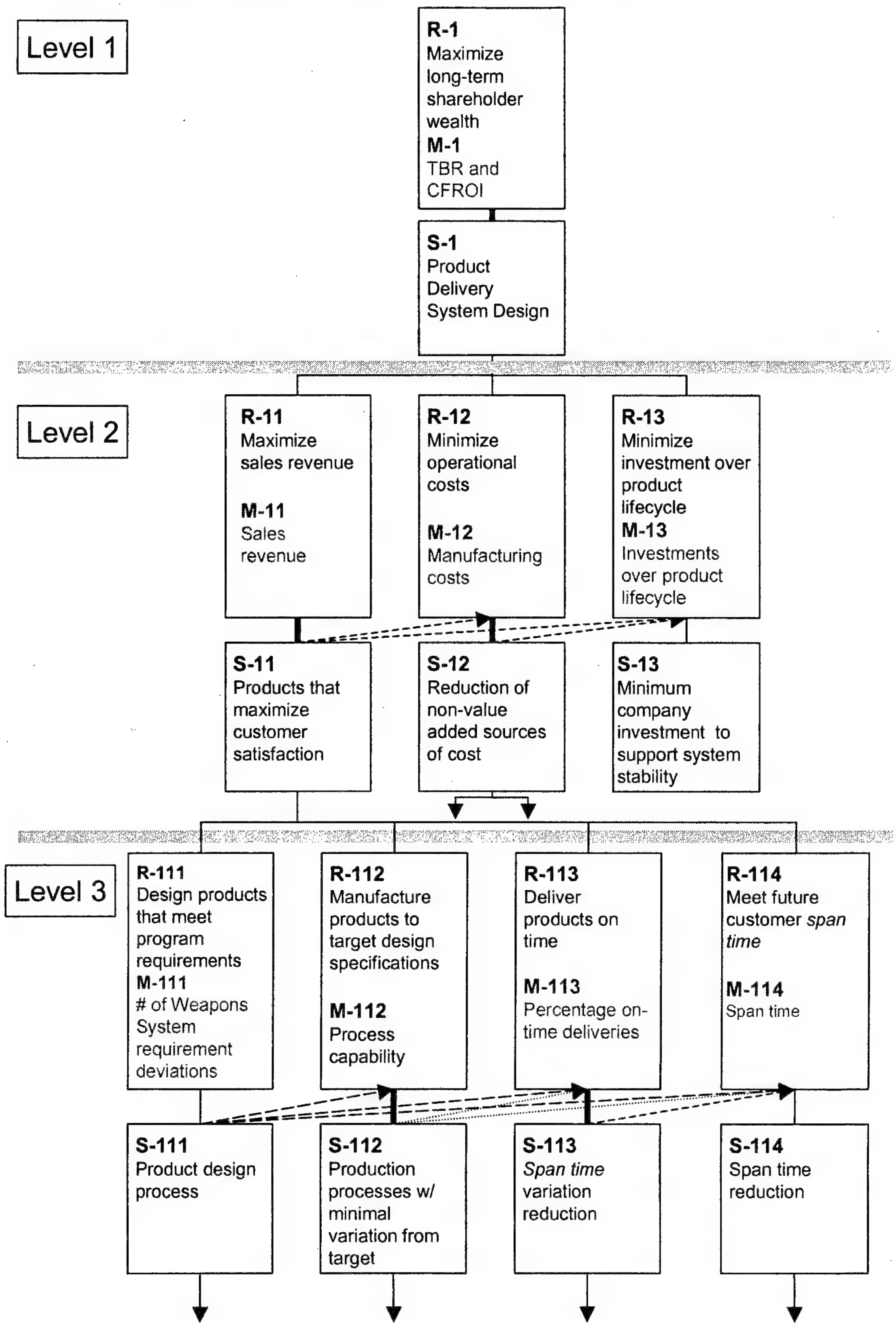
Axiomatic Design

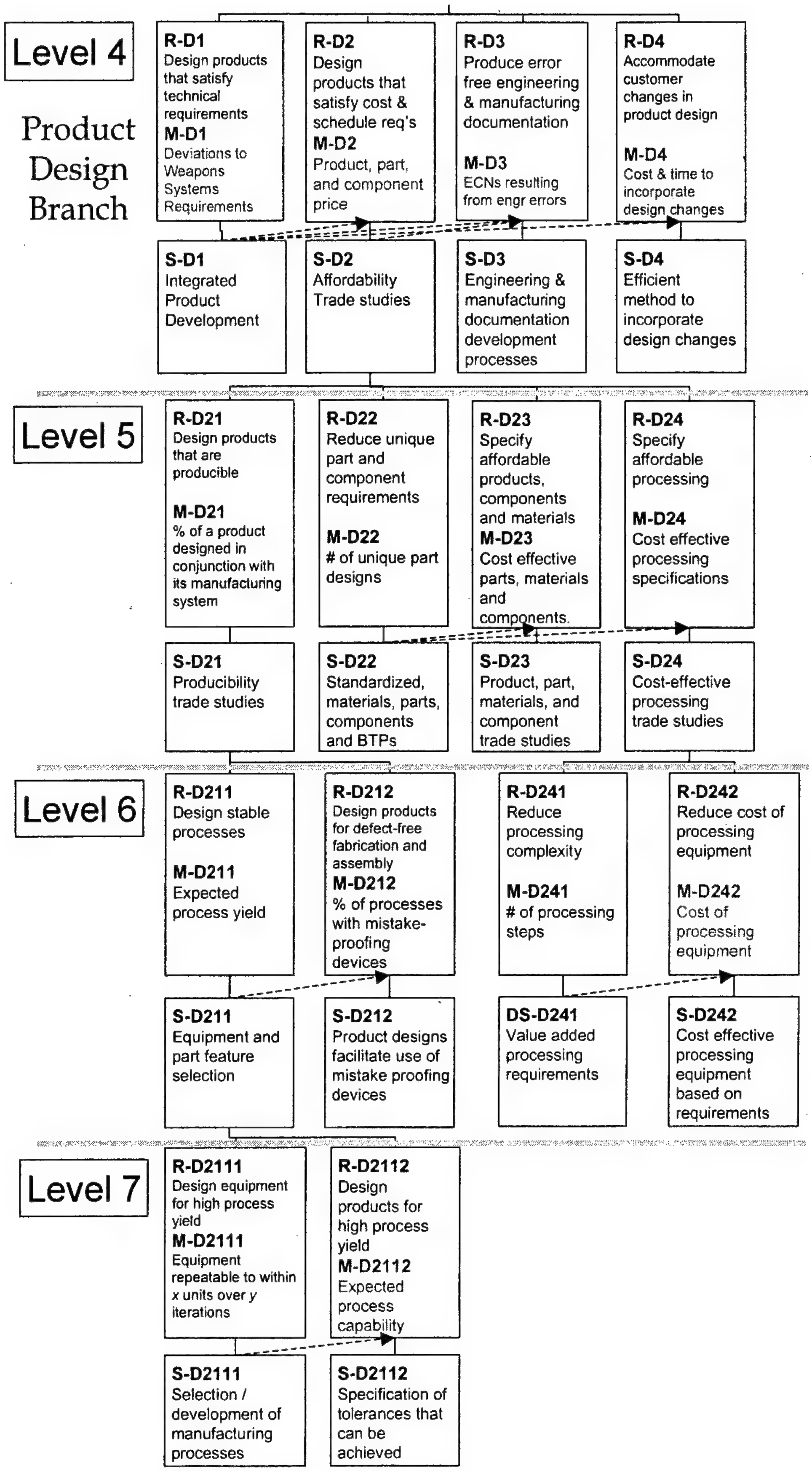
It is recommended that business schools begin to adopt axiomatic design as a part of their curriculums. Axiomatic design has proven to be a very powerful design methodology rich in application to the design of various fields. The teaching of axiomatic design, however, has proven to be difficult. Systems will not be properly designed until management understands, appreciates and actively enables the design effort. For this to occur, management, usually not having a technical background, must be able to grasp axiomatic design concepts.

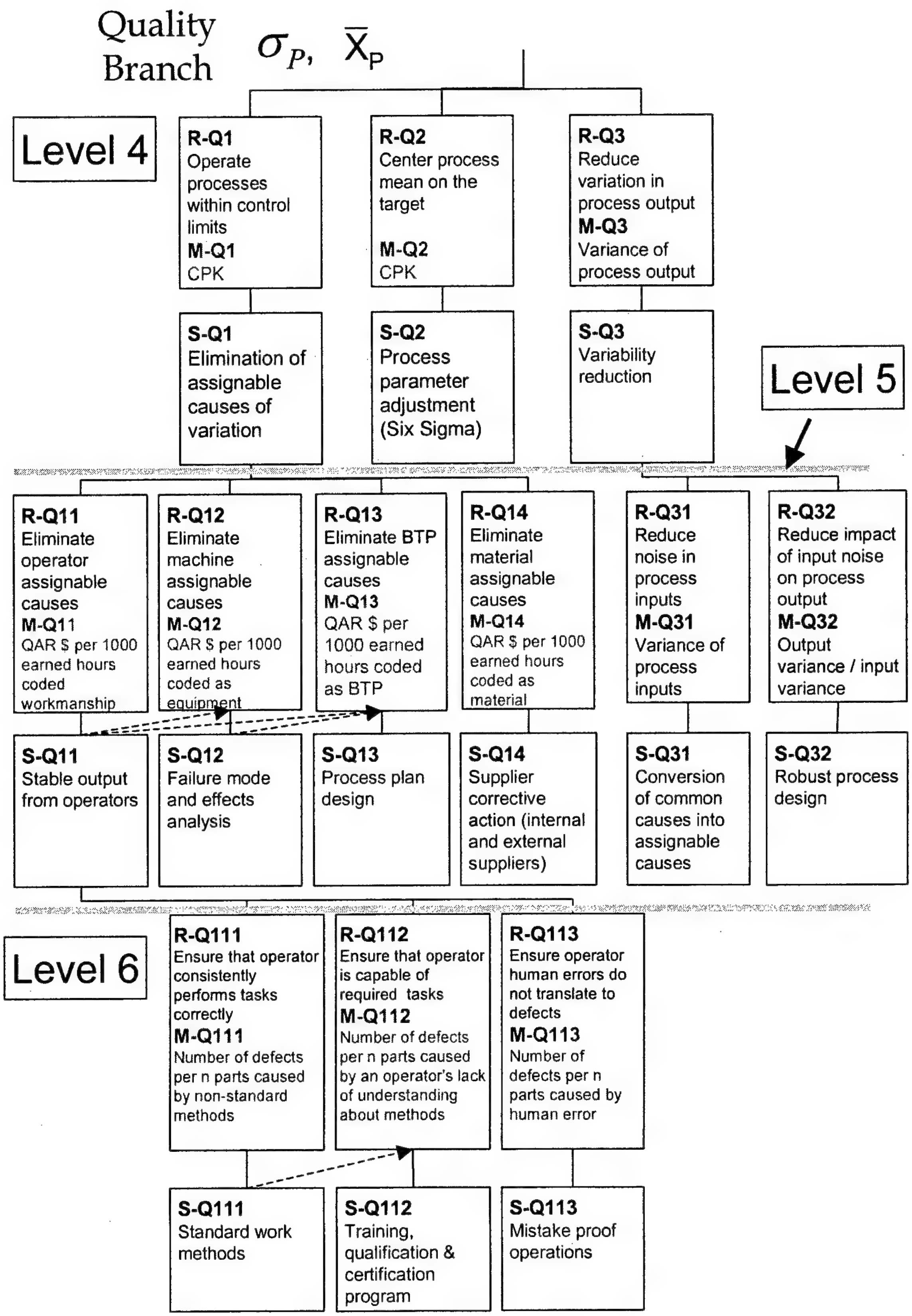
Current State Problem Understanding and Acceptance

Further research is recommended in the combined use of system dynamics to identify and teach the current state problem, and axiomatic design to logically identify the ideal future system design. Implementation of the system design process is predicated on the consensus that all participants must fully understand and appreciate the poor design of the current state system. There must be acceptance that the system is out of control and that the current methods of solving the problem are inadequate. Therefore teaching of the very existence and magnitude of the importance must precede the teaching of the solution as defined by axiomatic design.

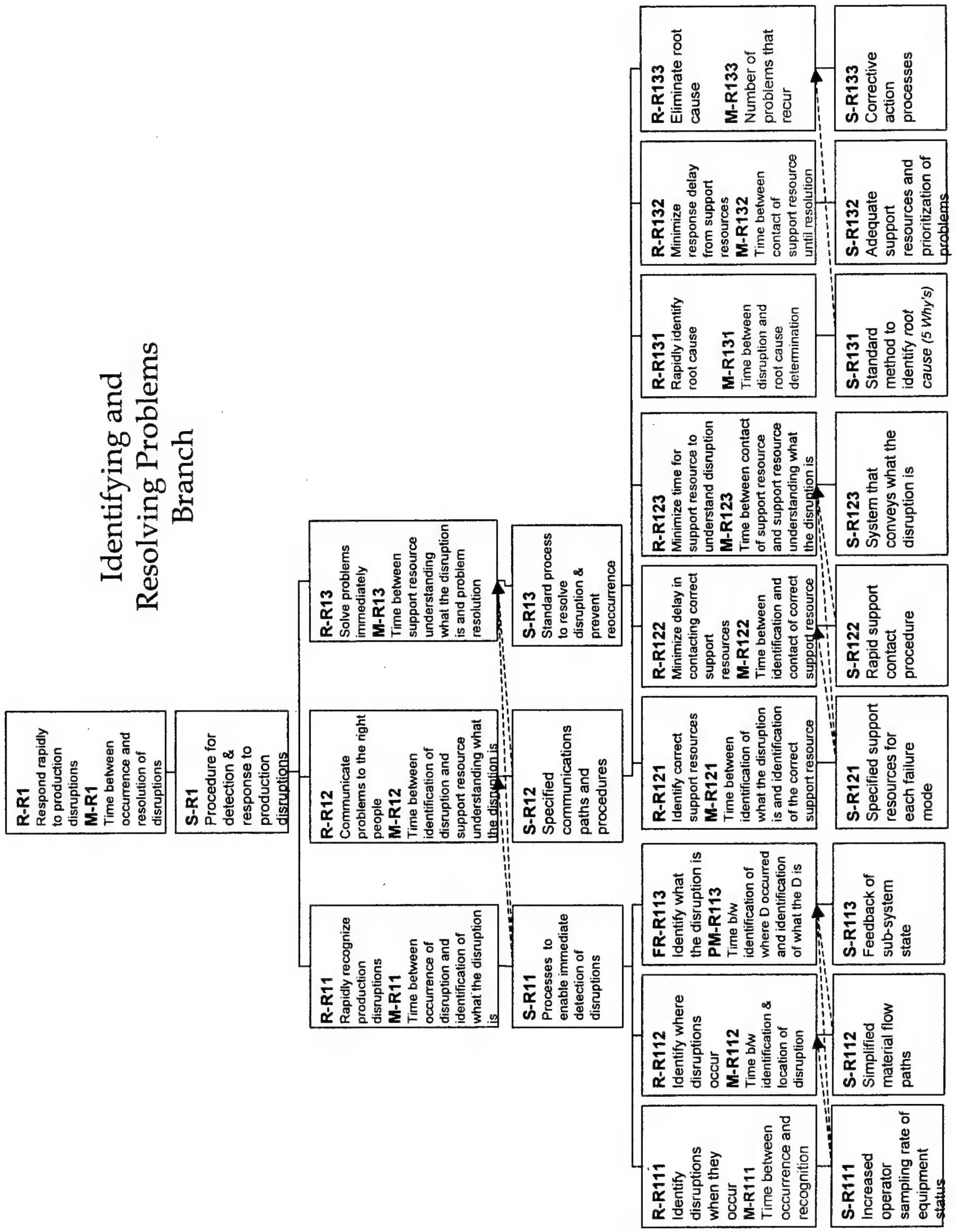
APPENDIX A: THE PRODUCT DELIVERY SYSTEM (PDS)

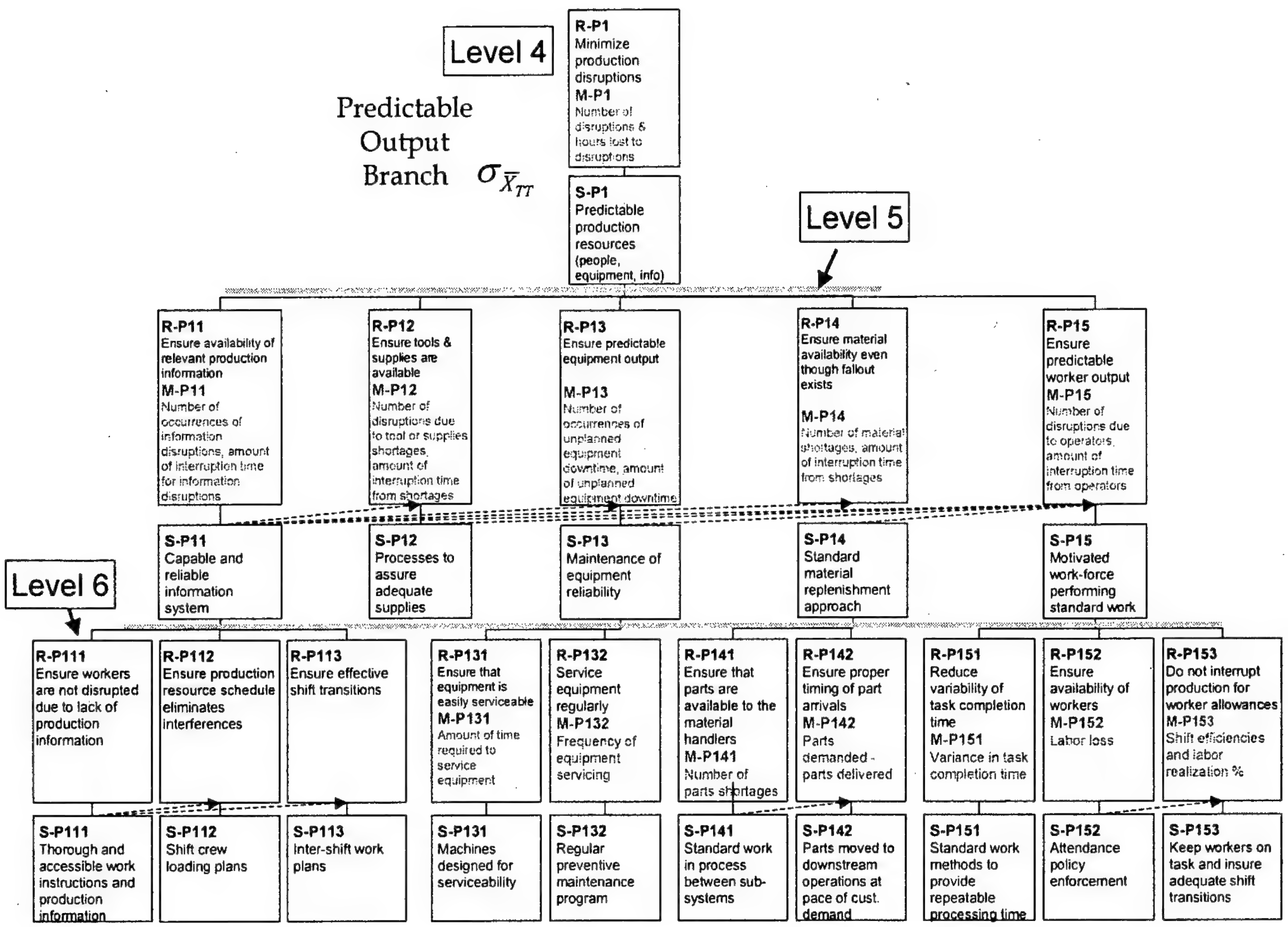


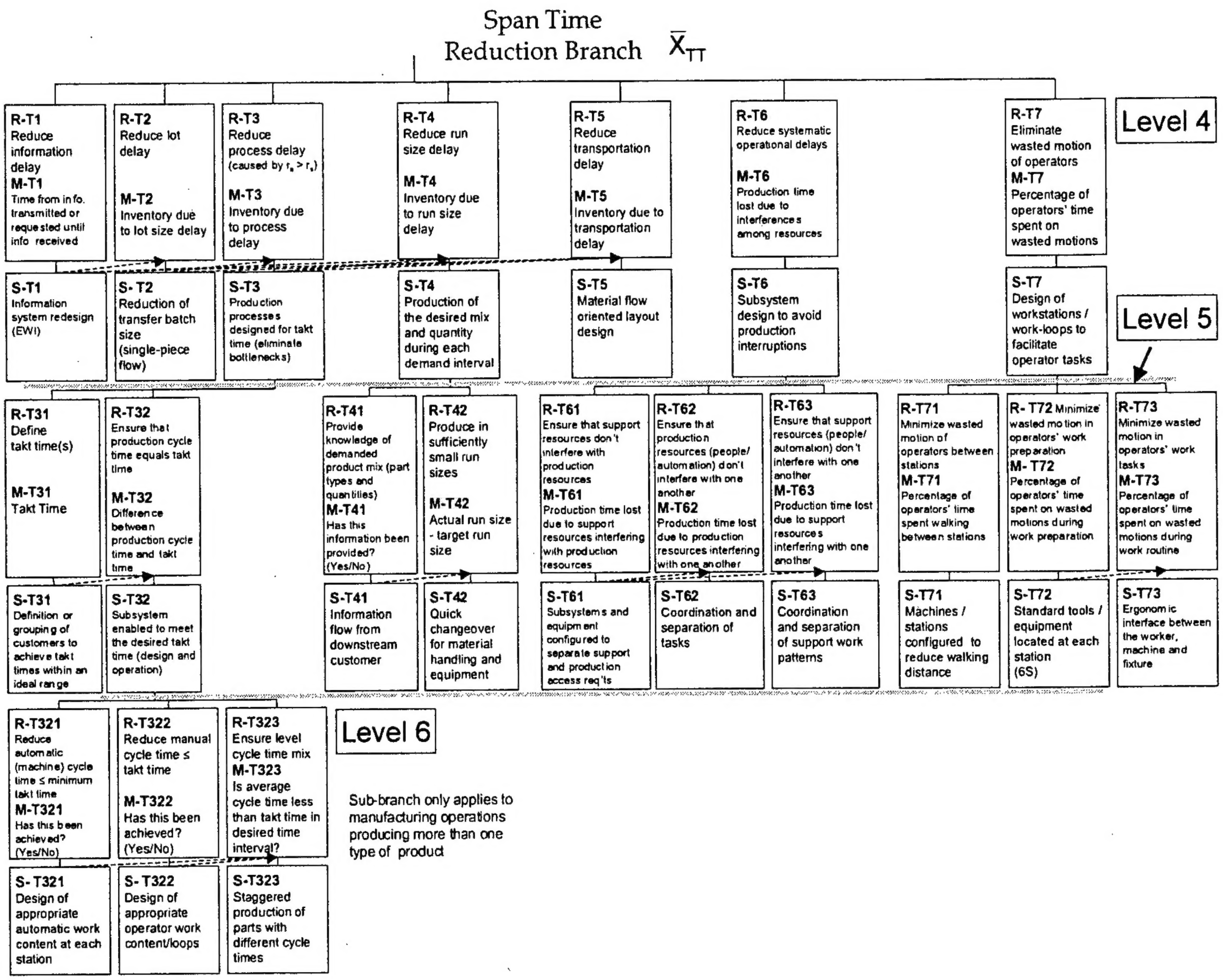

Level 4
Product Design Branch
R-D1 Design products that satisfy technical requirements M-D1 Deviations to Weapons Systems Requirements
R-D2 Design products that satisfy cost & schedule req's M-D2 Product, part, and component price
R-D3 Produce error free engineering & manufacturing documentation M-D3 ECNs resulting from engr errors
R-D4 Accommodate customer changes in product design M-D4 Cost & time to incorporate design changes
S-D1 Integrated Product Development
S-D2 Affordability Trade studies
S-D3 Engineering & manufacturing documentation development processes
S-D4 Efficient method to incorporate design changes
Level 5
R-D21 Design products that are producible M-D21 % of a product designed in conjunction with its manufacturing system
R-D22 Reduce unique part and component requirements M-D22 # of unique part designs
R-D23 Specify affordable products, components and materials M-D23 Cost effective parts, materials and components.
R-D24 Specify affordable processing M-D24 Cost effective processing specifications
S-D21 Producibility trade studies
S-D22 Standardized, materials, parts, components and BTPs
S-D23 Product, part, materials, and component trade studies
S-D24 Cost-effective processing trade studies
Level 6
R-D211 Design stable processes M-D211 Expected process yield
R-D212 Design products for defect-free fabrication and assembly M-D212 % of processes with mistake-proofing devices
R-D241 Reduce processing complexity M-D241 # of processing steps
R-D242 Reduce cost of processing equipment M-D242 Cost of processing equipment
S-D211 Equipment and part feature selection
S-D212 Product designs facilitate use of mistake proofing devices
DS-D241 Value added processing requirements
S-D242 Cost effective processing equipment based on requirements
Level 7
R-D2111 Design equipment for high process yield M-D2111 Equipment repeatable to within x units over y iterations
R-D2112 Design products for high process yield M-D2112 Expected process capability
S-D2111 Selection / development of manufacturing processes
S-D2112 Specification of tolerances that can be achieved

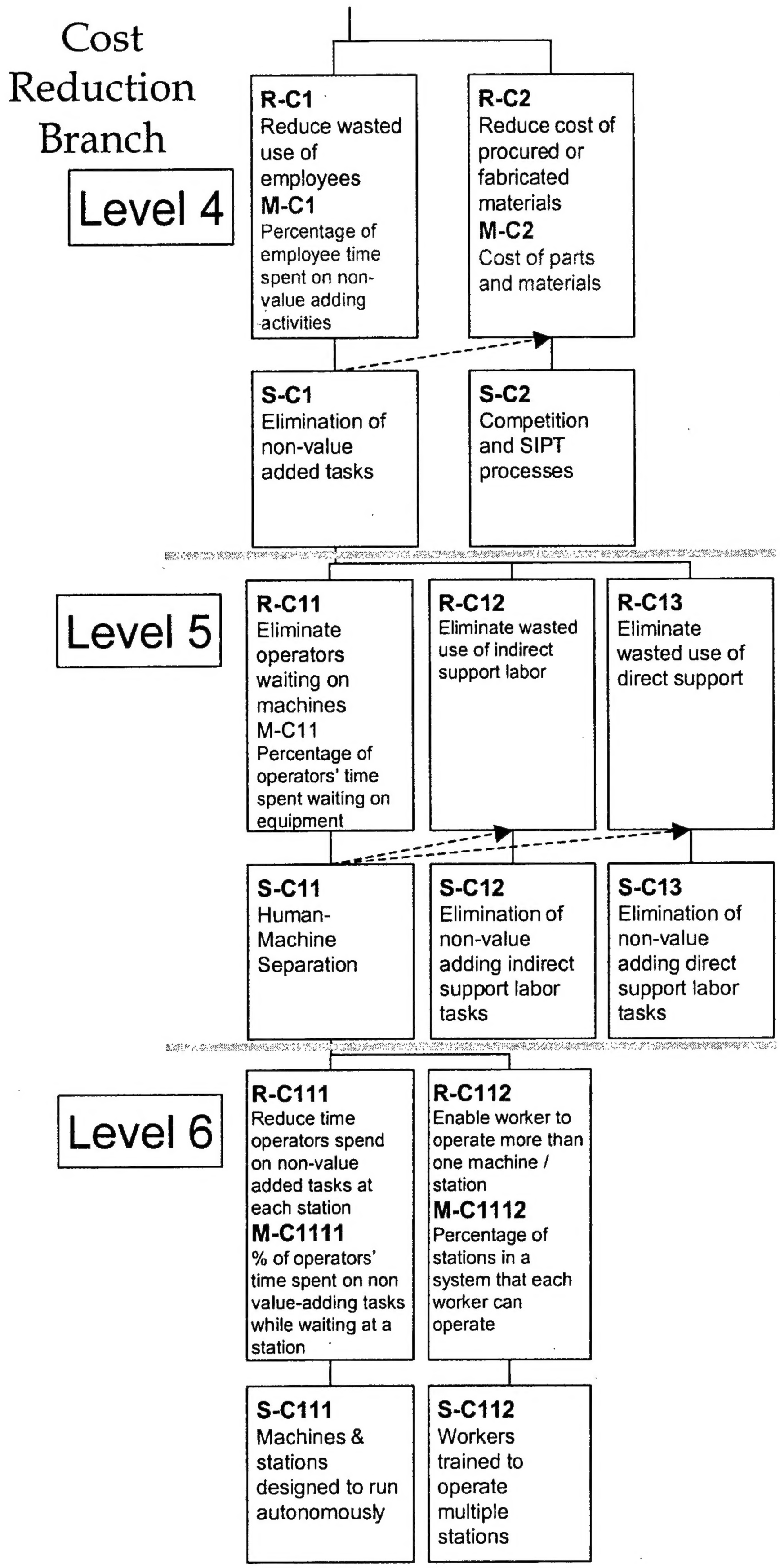


Quality Branch
σ_P, $\overline{X}_P$
Level 4
R-Q1 Operate processes within control limits
M-Q1 CPK
R-Q2 Center process mean on the target
M-Q2 CPK
R-Q3 Reduce variation in process output
M-Q3 Variance of process output
S-Q1 Elimination of assignable causes of variation
S-Q2 Process parameter adjustment (Six Sigma)
S-Q3 Variability reduction
Level 5
R-Q11 Eliminate operator assignable causes
M-Q11 QAR $ per 1000 earned hours coded workmanship
R-Q12 Eliminate machine assignable causes
M-Q12 QAR $ per 1000 earned hours coded as equipment
R-Q13 Eliminate BTP assignable causes
M-Q13 QAR $ per 1000 earned hours coded as BTP
R-Q14 Eliminate material assignable causes
M-Q14 QAR $ per 1000 earned hours coded as material
R-Q31 Reduce noise in process inputs
M-Q31 Variance of process inputs
R-Q32 Reduce impact of input noise on process output
M-Q32 Output variance / input variance
S-Q11 Stable output from operators
S-Q12 Failure mode and effects analysis
S-Q13 Process plan design
S-Q14 Supplier corrective action (internal and external suppliers)
S-Q31 Conversion of common causes into assignable causes
S-Q32 Robust process design
Level 6
R-Q111 Ensure that operator consistently performs tasks correctly
M-Q111 Number of defects per n parts caused by non-standard methods
R-Q112 Ensure that operator is capable of required tasks
M-Q112 Number of defects per n parts caused by an operator's lack of understanding about methods
R-Q113 Ensure operator human errors do not translate to defects
M-Q113 Number of defects per n parts caused by human error
S-Q111 Standard work methods
S-Q112 Training, qualification & certification program
S-Q113 Mistake proof operations


Identifying and Resolving Problems Branch
R-R1 Respond rapidly to production disruptions M-R1 Time between occurrence and resolution of disruptions
S-R1 Procedure for detection & response to production disruptions
R-R11 Rapidly recognize production disruptions M-R11 Time between occurrence of disruption and identification of what the disruption is
R-R12 Communicate problems to the right people M-R12 Time between identification of disruption and support resource understanding what the disruption is
R-R13 Solve problems immediately M-R13 Time between support resource understanding what the disruption is and problem resolution
S-R11 Processes to enable immediate detection of disruptions
S-R12 Specified communications paths and procedures
S-R13 Standard process to resolve disruption & prevent reoccurrence
R-R111 Identify disruptions when they occur M-R111 Time between occurrence and recognition
R-R112 Identify where disruptions occur M-R112 Time b/w identification & location of disruption
FR-R113 Identify what the disruption is PM-R113 Time b/w identification of where D occurred and identification of what the D is
R-R121 Identify correct support resources M-R121 Time between identification of what the disruption is and identification of the correct support resource
R-R122 Minimize delay in contacting correct support resources M-R122 Time between identification and contact of correct support resource
R-R123 Minimize time for support resource to understand disruption M-R123 Time between contact of support resource and support resource understanding what the disruption is
R-R131 Rapidly identify root cause M-R131 Time between disruption and root cause determination
R-R132 Minimize response delay from support resources M-R132 Time between contact of support resource until resolution
R-R133 Eliminate root cause M-R133 Number of problems that recur
S-R111 Increased operator sampling rate of equipment status
S-R112 Simplified material flow paths
S-R113 Feedback of sub-system state
S-R121 Specified support resources for each failure mode
S-R122 Rapid support contact procedure
S-R123 System that conveys what the disruption is
S-R131 Standard method to identify root cause (5 Why's)
S-R132 Adequate support resources and prioritization of problems
S-R133 Corrective action processes


Level 4
Predictable Output Branch $\sigma_{\overline{X}_{TT}}$
R-P1 Minimize production disruptions
M-P1 Number of disruptions & hours lost to disruptions
S-P1 Predictable production resources (people, equipment, info)
Level 5
R-P11 Ensure availability of relevant production information
M-P11 Number of occurrences of information disruptions, amount of interruption time for information disruptions
R-P12 Ensure tools & supplies are available
M-P12 Number of disruptions due to tool or supplies shortages, amount of interruption time from shortages
R-P13 Ensure predictable equipment output
M-P13 Number of occurrences of unplanned equipment downtime, amount of unplanned equipment downtime
R-P14 Ensure material availability even though fallout exists
M-P14 Number of material shortages, amount of interruption time from shortages
R-P15 Ensure predictable worker output
M-P15 Number of disruptions due to operators, amount of interruption time from operators
S-P11 Capable and reliable information system
S-P12 Processes to assure adequate supplies
S-P13 Maintenance of equipment reliability
S-P14 Standard material replenishment approach
S-P15 Motivated work-force performing standard work
Level 6
R-P111 Ensure workers are not disrupted due to lack of production information
R-P112 Ensure production resource schedule eliminates interferences
R-P113 Ensure effective shift transitions
R-P131 Ensure that equipment is easily serviceable
M-P131 Amount of time required to service equipment
R-P132 Service equipment regularly
M-P132 Frequency of equipment servicing
R-P141 Ensure that parts are available to the material handlers
M-P141 Number of parts shortages
R-P142 Ensure proper timing of part arrivals
M-P142 Parts demanded - parts delivered
R-P151 Reduce variability of task completion time
M-P151 Variance in task completion time
R-P152 Ensure availability of workers
M-P152 Labor loss
R-P153 Do not interrupt production for worker allowances
M-P153 Shift efficiencies and labor realization %
S-P111 Thorough and accessible work instructions and production information
S-P112 Shift crew loading plans
S-P113 Inter-shift work plans
S-P131 Machines designed for serviceability
S-P132 Regular preventive maintenance program
S-P141 Standard work in process between sub-systems
S-P142 Parts moved to downstream operations at pace of cust. demand
S-P151 Standard work methods to provide repeatable processing time
S-P152 Attendance policy enforcement
S-P153 Keep workers on task and insure adequate shift transitions


Span Time
Reduction Branch $\overline{X}_{TT}$
Level 4
Level 5
Level 6
R-T1 Reduce information delay
M-T1 Time from info. transmitted or requested until info received
R-T2 Reduce lot delay
M-T2 Inventory due to lot size delay
R-T3 Reduce process delay (caused by $r_a > r_s$)
M-T3 Inventory due to process delay
R-T4 Reduce run size delay
M-T4 Inventory due to run size delay
R-T5 Reduce transportation delay
M-T5 Inventory due to transportation delay
R-T6 Reduce systematic operational delays
M-T6 Production time lost due to interferences among resources
R-T7 Eliminate wasted motion of operators
M-T7 Percentage of operators' time spent on wasted motions
S-T1 Information system redesign (EWI)
S-T2 Reduction of transfer batch size (single-piece flow)
S-T3 Production processes designed for takt time (eliminate bottlenecks)
S-T4 Production of the desired mix and quantity during each demand interval
S-T5 Material flow oriented layout design
S-T6 Subsystem design to avoid production interruptions
S-T7 Design of workstations / work-loops to facilitate operator tasks
R-T31 Define takt time(s)
M-T31 Takt Time
R-T32 Ensure that production cycle time equals takt time
M-T32 Difference between production cycle time and takt time
R-T41 Provide knowledge of demanded product mix (part types and quantities)
M-T41 Has this information been provided? (Yes/No)
R-T42 Produce in sufficiently small run sizes
M-T42 Actual run size - target run size
R-T61 Ensure that support resources don't interfere with production resources
M-T61 Production time lost due to support resources interfering with production resources
R-T62 Ensure that production resources (people/ automation) don't interfere with one another
M-T62 Production time lost due to production resources interfering with one another
R-T63 Ensure that support resources (people/ automation) don't interfere with one another
M-T63 Production time lost due to support resources interfering with one another
R-T71 Minimize wasted motion of operators between stations
M-T71 Percentage of operators' time spent walking between stations
R-T72 Minimize wasted motion in operators' work preparation
M-T72 Percentage of operators' time spent on wasted motions during work preparation
R-T73 Minimize wasted motion in operators' work tasks
M-T73 Percentage of operators' time spent on wasted motions during work routine
S-T31 Definition or grouping of customers to achieve takt times within an ideal range
S-T32 Subsystem enabled to meet the desired takt time (design and operation)
S-T41 Information flow from downstream customer
S-T42 Quick changeover for material handling and equipment
S-T61 Subsystems and equipment configured to separate support and production access req'ts
S-T62 Coordination and separation of tasks
S-T63 Coordination and separation of support work patterns
S-T71 Machines / stations configured to reduce walking distance
S-T72 Standard tools / equipment located at each station (6S)
S-T73 Ergonomic interface between the worker, machine and fixture
R-T321 Reduce automatic (machine) cycle time ≤ minimum takt time
M-T321 Has this been achieved? (Yes/No)
R-T322 Reduce manual cycle time ≤ takt time
M-T322 Has this been achieved? (Yes/No)
R-T323 Ensure level cycle time mix
M-T323 Is average cycle time less than takt time in desired time interval?
Sub-branch only applies to manufacturing operations producing more than one type of product
S-T321 Design of appropriate automatic work content at each station
S-T322 Design of appropriate operator work content/loops
S-T323 Staggered production of parts with different cycle times


Cost Reduction Branch
Level 4
R-C1 Reduce wasted use of employees
M-C1 Percentage of employee time spent on non-value adding activities
R-C2 Reduce cost of procured or fabricated materials
M-C2 Cost of parts and materials
S-C1 Elimination of non-value added tasks
S-C2 Competition and SIPT processes
Level 5
R-C11 Eliminate operators waiting on machines
M-C11 Percentage of operators' time spent waiting on equipment
R-C12 Eliminate wasted use of indirect support labor
R-C13 Eliminate wasted use of direct support
S-C11 Human-Machine Separation
S-C12 Elimination of non-value adding indirect support labor tasks
S-C13 Elimination of non-value adding direct support labor tasks
Level 6
R-C111 Reduce time operators spend on non-value added tasks at each station
M-C1111 % of operators' time spent on non value-adding tasks while waiting at a station
R-C112 Enable worker to operate more than one machine / station
M-C1112 Percentage of stations in a system that each worker can operate
S-C111 Machines & stations designed to run autonomously
S-C112 Workers trained to operate multiple stations

REFERENCES

American Heritage (2000), *Dictionary of the English Language*, Fourth Edition, Houghton Mifflin Company.

Boppe, Charles, ESD33J System Engineering, class lecture, 2001, MIT.

Chryssolouris, G. (1992), *Manufacturing Systems: Theory and Practice*, Springer-Verlag, New York.

Cable News Network, (2001), *Europe lands U.S. fighter boost*, www.cnn.com.

Cochran, D., (1994), *The Design and Control of Manufacturing Systems*, Ph.D. Thesis, Auburn University.

Cochran, D., (1999), *The Production System Design and Deployment Framework*, SAE International Automotive Manufacturing Conference.

Cochran, D., Arinez, J., Duda, J., Linck, J., (2000), *A Decomposition Approach for Manufacturing System Design*, to appear in Journal of Manufacturing Systems.

Cochran, D., Isaacs, William, Won J. (April, 2002), System Design and Leadership - Learning Notes, presented to NASA and Lockheed Martin, MIT.

Cochran, D., Kim, Y.S., Kim J., (2000), The Impact of Performance Measurement on Manufacturing System Design, First International Conference on Axiomatic Design 2000.

Cochran, D., Ng, Q., Hendricks, S.D., Rudolf, H., (2002) *Investment and Resource Allocation Methodology to Support Manufacturing System Design Implementation*, submitted to the Journal of Manufacturing Systems, MIT.

Cochran, D., Won, J. (2002). *The 4+10 Process: A General Approach to System Design and Implementation*, Working Paper, MIT.

Deming, W. E., (2000), *Out of the Crisis*, MIT Press.

Crawley – IAP4

Frieberg, J., Frieberg, K., (1998), *Nuts! Southwest Airlines' Crazy Recipe for Business and Personal Success*, Broadway Books, New York, NY.

Hayes, R., Wheelwright, S. (1984), *Restoring our Competitive Edge – Competing through Manufacturing*, John Wiley & Sons.

Hopp, W., Spearman, M., (1996), *Factory Physics*, Irwin/McGraw-Hill, Boston, MA.

Johnson, H.T., Broms, A., (2000), *Profit Beyond Measure*, The Free Press, New York, NY.

Johnson, H.T., Kaplan, R. S., (1987) *Relevance Lost: The Rise and Fall of Management Accounting*, Harvard Business School Press, Boston, MA.

Kuo, Benjamin D., (1992), *Automatic Control Systems: Sixth Edition*, Prentice Hall, Englewood Cliffs, NJ.

Linck, J. (2001), *A Decomposition-Based Approach for Manufacturing System Design*, Ph.D. Thesis, Massachusetts Institute of Technology.

Maskell, B.H., (1991), *Performance Measurement for World Class Manufacturing: A Model for American Companies*, Productivity Press, Cambridge, MA.

Monden, Y., (1998), *Toyota Production System: An Integrated Approach to Just-in-Time*, Third Edition, Engineering & Management Press, Norcross, Georgia.

Parnaby, J. (1979), *Concept of a Manufacturing System*, International Journal of Production Research, Vol. 17, No. 2, 123-135.

Roche, James G., Secretary of the Air Force – speech at Harvard University, March 2002.

Schonberger, R., (1996), *World Class Manufacturing: The Next Decade*, Simon & Schuster, New York, NY.

Senge, P. (1994), *The Fifth Discipline: The Art and Practice of the Learning Organization*, Currency/Doubleday.

Spear, S., (1999), *The Toyota Production System: An Example of Managing Complex Social/Technical System – 5 Rules for Designing, Operating, and Improving Activities, Activity-Connections, and Flow-Paths*, Ph.D. thesis, Harvard University.

Suh, N.P. (1990), *The Principles of Design*, New York: Oxford University Press.

Suh, N.P. (2001), *Axiomatic Design: Advances and Applications*, Oxford University Press, New York, NY.

Suh, N.P. (2002), lecture to NASA

Webster's Revised Unabridged Dictionary, (1998) MICRA, Inc.

Womack, J. (2002) – course lecture, MIT.

Womack, J., Jones, D., Roos, D., (1990), *The Machine That Changed the World*, Harper Perennial, New York, NY.

Won, J., Cochran, D., Johnson, H.T., Bouzekouk, S., Masha, B., (2001), *Rationalizing the Design of the Toyota Production System: A Comparison of Two Approaches*, International CIRP Design Seminar 2001.

Wu, B. (1992), *Manufacturing Systems Design and Analysis*, Second Edition, Chapman and Hall, London.